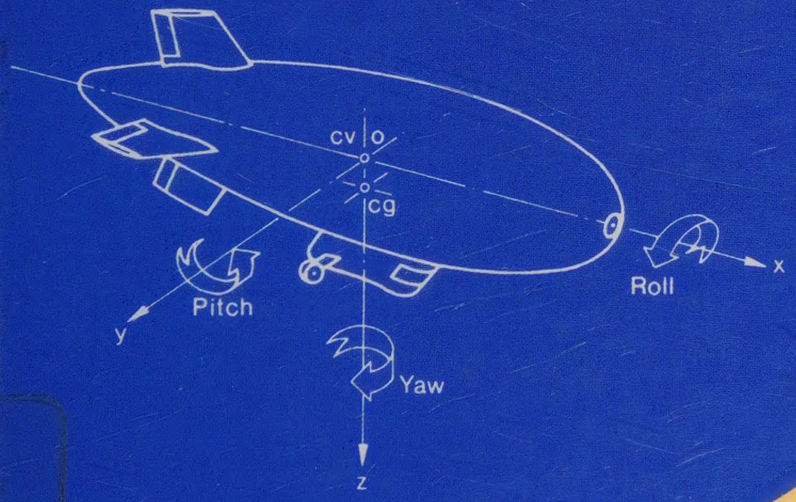
Airship Technology

Edited by Gabriel A. Khoury and J. David Gillett



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This book provides a unique and indispensable guide to modern airship design and operation.

Airships today incorporate advanced technology including composite materials, complex electronic systems and fly-by-light controls. They demand the latest theories in aerodynamics, stability and control and require the use of advanced design tools such as numerical finite element structural analysis and computer aided design. This comprehensive and fully illustrated account brings together airship specialists from both universities and industry. After a general introduction, the essentials of aerostatics, aerodynamics, stability and control, propulsion, materials and structures are covered. The following chapters consider weight estimates and control, ground handling and mooring, systems, performance and piloting. The final chapters examine suggestions for improving airship performance, survey unconventional designs, synthesise various design elements, and look at airship roles and economic considerations vital for the success of the airship in the market place. Detailed references are also included.

This book will be of interest to airship designers and engineers, professional and student aeronautical engineers, and also to airship enthusiasts.

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Airship Technology

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Airship Technology

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Contents

Preface

Revival of serious interest in airships in the UK by both industrialists and academics has taken place in the early 1970s with the formation of the international Airship Association and with the quarterly publication of its Journal *Airship*. Annual symposia have since been held at the Royal Aeronautical Society and, subsequently, the Airship Association enlarged this activity by holding its International Conventions and Exhibitions in Bedford, England, not far from the two famous airship hangers. Recently, the Airship Association has also set up a dedicated web site on the internet (http://www.airship.demon.co.uk). During this period, the design and development of state-of-the-art non-rigid airships for civil and military applications in the UK owed much to the efforts of Mr Roger Munk to whom this book is dedicated. Whether in design and development, or merely in operation, airship activity has also taken place in many other countries including Australia, Canada, China, Brazil, Germany, Hungary, Italy, Japan, Mexico, New Zealand, Russia, South Africa, and the USA.

Given the increased activity world-wide, there is an urgent need for an up-to-date detailed technical book on this subject. Modern airships employ advanced technologies such as composite materials, numerical finite element structural analysis, computer aided design, modern electronic systems, fly-by-light controls and the latest theories in aerodynamics as well as stability and control. Yet today's airship designers have only textbooks published in the 1920s and 1930s for reference, namely by Burgess: *Airship Design* (1927), Blakemore: *Pressure Airships Part I* (1927), Pagon: *Pressure Airships Part II* (1927), and Durand: *Aerodynamic Theory* (1937).

This book, therefore, draws on recent experience by bringing together fourteen specialists in different aspects of airship design and operation. These experts were drawn equally from academia and industry thus providing the appropriate balance of theory and practice. Academics contribute the chapters *Basic Principles* (Dr Edwin Mowforth), *Aerodynamics* (Professor Ian Cheeseman), *Stability & Control* (Mr Michael Cook), *Propulsion* (Professor Ian Cheeseman), *Ground Handling & Mooring* (Professor Denis Howe), *Improvements* (Dr Edwin Mowforth), *Unconventional Designs* (Dr Gabriel Khoury), and *Solar Power* (Dr Gabriel Khoury). Industrialists contribute the chapters *Materials* (Dr Peter Bradley), *Structures* (Mr Charles Luffman), *Aerostatics* (Mr John Craig), *Weight Estimates & Control* (Mr John Craig), *Systems* (Mr Norman Mayer), *Piloting* (Mr David Burns), *Performance* (Mr Robert Hunt), *Roles & Economic Considerations* (Mr Reginald Hillsdon), and *Design Synthesis* (Mr Brian Wilson).

Gabriel A. Khoury
J. David Gillett

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The editors wish to express their appreciation to the other authors of the different chapters for their co-operation and valuable contributions.

The contribution of The Airship Association - direct and indirect - is also very much appreciated. Mr Dick Chadburn, Chairman of the Association, has kindly granted permission for the use of diagrams from the Association's publications.

The assistance of Westinghouse Surveillance Ltd. in furnishing information and diagrams on the Skyships series of airships for a number of chapters in this book is gratefully acknowledged. Contributors of other graphical material are also gratefully acknowledged. These include The Imperial War Museum, Mr Nigel Wells, Dr J. Bracher, Dr Masahiko Onda, Zeppelin Luftschiffstechnik, Dr Edwin Mowforth, and Professor J. DeLaurier.

A special note of thanks is reserved for the professional skills of Mrs Valerie Till who has re-drawn nearly 200 line drawings and graphs. This has contributed so much to the consistent appearance of the book and to the high quality of its diagrams.

Last but not least, we thank our wives Adriene and Irena for their patience during the many years of preparation of this book.

POSTSCRIPT

Sadly, my co-editor and good friend Professor J. David Gillett OBE, DSc died on the 14th of October 1995 aged 82 before publication of this book. Professor Gillett was a distinguished scientist, a former Pro-Vice-Chancellor of Brunel University and President of the Royal Entomological Society. From his early days, Gillett was intrigued by airships, having observed the giants of the sky including the British R33, R34, R36, R100 and R101 and the German Graf Zeppelin. Gillett was a founding member of the Airship Association (1971) and served with me on its Technical Committee. He was elected member of council and Vice-Chairman of the Association, in which capacities he served until he died.

This book is dedicated to
Mr Roger Munk
for his contributions to the design and development of the modern airship

1

Introduction

G.A. Khoury and J.D. Gillett

This book is intended as a technical guide to those interested in designing, building and flying the airship of today. While aiming towards thc future, mention is made - where appropriate - of the experience of earlier years when these point up relevant information.

Modern airships employ advanced technologies such as composite materials, computerised numerical finite element structural analysis, computer aided design, modern electronic systems, fly-by-light controls and the latest theories in aerodynamics as well as stability and control. Some aspects of modern design are borrowed from other disciplines while in certain areas such as envelope fabrics and automatic docking systems the technology is specifically developed for the airship. Mainstream aeronautical data are available in numerous publications and are not duplicated herein. This book is, therefore, devoted to those aspects of design and operation that are particular to airships.

A distinguishing feature of airships is their reliance on a light gas for lift. It is, therefore, necessary that all those involved with airships have a good understanding of the basic principles of aerostatics. A brief outline of the subject is given in Chapter 2 on *Basic Principles* and a more detailed treatment is given in Chapter 8 on *Aerostatics*.

The bare hull of the conventional airship is of the classic streamline form. The conventional airship is, however, essentially a low-speed vehicle with the power requirement being approximately proportional to the cube of the airspeed. Higher speeds require a rapid escalation of weight and fuel consumption, while structure weight increases to meet the higher aerodynamic loading. Despite elegant streamlining, the aerodynamic drag of an airship is high. For a typical airship in steady axial flight, part of the total aerodynamic drag owes its origin to the bare hull and the remainder is generated by fins, engines and the control car. The latter appendages produce drag not only because of their own resistance but also through their interference with the flow over the main hull. The 'bare hull' drag could account for about 60-70% of the total, the proportion increasing with airship size as the appendages become smaller in relation to the hull. The aerodynamics of airships is briefly discussed in Chapter 2 (*Basic Principles*) and in more detail in Chapter 3 (*Aerodynamics*). Boundary layer control is also discussed in Chapter 14 on *Improvements*.

The most significant contribution to the development of the *Stability and Control* of the modern airship (Chapter 4), stems from advancements in computer technology. It is now feasible to undertake hitherto difficult, if not impossible, analysis and simulation which has enabled the attainment of new levels of insight and understanding. This in turn has encouraged the development of more detailed and more accurate aerodynamic and dynamic models of the airship culminating in extremely comprehensive non-linear simulation models. The digital computer is now also firmly established for the control of air vehicles and is the nucleus of the EFCS (electronic flight control systems), which can be used to very good effect in the airship. The euphoria, however, is tempered when it is realised that the performance of the EFCS is limited by the effectiveness of the aerodynamic control surfaces it drives. New developments may overcome this limitation to a certain extent by integrating control of the propulsion unit thrust vectoring into the overall control strategy.

The importance of good *Weight Estimates and Control* (Chapter 9) during all phases of the design of an airship, especially in the early stages, cannot be over-emphasised. The amount by which the airship is 'overweight' has a more direct effect on the performance than it would on a conventional fixed- or rotary-winged vehicle. Every additional kilogram of weight is one kilogram lost in available payload. Also, because an airship is very fuel efficient, any lost fuel capacity through this increased weight has an effect on endurance, which can be several orders of magnitude greater than for a heavier-than-air aircraft. Because endurance is one of the primary benefits of an airship - and in many cases its sole *raison d'être* - accurate preliminary weight estimation, and strict weight control, are vital.

Many of the major developments in materials of this century, particularly in the areas of specific strength, have been instigated by the aerospace industries. These developments/advances have fundamentally changed the design of aircraft. The introduction of such materials as lightweight strong alloys, fibre reinforced composites or honeycomb materials have all had major impacts on the design of aircraft structures while improvements in high temperature properties through alloy development and manufacturing methods (e.g. directionally cast, single crystal, or metal matrix composite turbine blades) have transformed engine technology. Most of these developments, and especially the introduction of stronger lighter materials (e.g. Kevlar) have helped airship design through lighter gondolas, nose cones, battens and tail fins. These consequences are a spin-off from material developments aimed at conventional airframe rather than as airship specific developments. However, it is major developments in textile engineering that have been uniquely responsible for advances in airship design, and for this reason Chapter 6 on *Materials* will consider those developments only. The advances in other structural materials have been adequately covered in other publications.

Airship *Structures* are described in Chapter 7. In earlier airships, stress analysis was conducted laboriously and manually with the risk of errors in the calculations ever being present. Structural analysis has since benefited considerably from the introduction of computerised finite element stress analysis methods. This added to the advances in material sciences, joining techniques, design aids, atmospheric awareness and aeronautics, allows the opportunity for efficient modern airships to be introduced at competitive prices.

Systems are the physical means of achieving a designed function. They consist of components, control mechanisms, and sensors. Some systems are essential to the operation of others, such as those that are power sources; examples being electrical, hydraulic, and pneumatic. Airship systems include most of the major and minor groups found on all aircraft and a few that are peculiar to lighter-than-air aircraft. The items described in Chapter 10 on *Systems* can be found on most airships but the design, complexity, and location may differ considerably from type to type. Some systems may be peculiar to airships designed for particular missions, such as an inflight replenishing in military applications. The major systems not covered in Chapter 10, such as *Stability and Control* and *Propulsion*, are instead described in Chapters 4 and 5 respectively.

The issue of *Ground Handling and Mooring* (Chapter 11) is still seen as one of the most problematic areas of airship operation. Significant improvements are, however, taking place in this area with the development of thrusters and automatic docking systems. The future solution of ground handling and mooring requirements is very closely associated with the provision of adequate control to enable precise low speed flight to be undertaken reliably and safely. Given this, the remaining issues are concerned with ensuring that the structure of the airship is of adequate strength to resist the loading anticipated whilst the craft is moored.

The tasks of the pilot described in detail in Chapter 12 on *Piloting* are valid for small and medium sized non-rigid airships up to about 20 000 m^3 volume. Non-rigid airships larger than this are likely to require amended techniques as they would exhibit different characteristics owing to their size, mass and inertia. Rigid airships will require different techniques owing to their greater options on ballast, mass, power plant and gondola (or car) locations, as did the great rigids of the past. The differences in piloting an airship from that of fixed- or rotary-wing flight includes lower speeds and slower responses, dependence on the availability of a ground handling party, and the possibly greater impact of certain meteorological conditions. Every landing is different owing to a combination of meteorological, locational and on-board factors. The airship pilot has, therefore, almost to become a part-time meteorologist. It appears that pilots of rotary-wing and fixed-wing aircraft can make equally good airship pilots. However, some pilots who have spent 20 years or more flying at 400 knots may experience more than a little difficulty in adjusting to the low speed environment and indeed may never quite master airship flying. Airship pilots would, however, benefit from at least some basic flying training in heavier-than-air craft, alongside which they will eventually have to operate.

The payload limitations of heavier-than-air aircraft are, in most cases, imposed by airfield performance and weight, altitude, and temperature limited climb considerations. In contrast, the payload of airships is generally limited by the gas lift available in the climatic conditions prevailing at the cruise flight altitude. This means that the key cruise altitude, temperature conditions, payload and mission profile must be established very early in the design process, as alterations to these can cause big changes to volume. Only at extremely short airfields does take-off performance become a limitation. This and other comparisons with heavier-than-air aircraft are explained in Chapter 13 on *Performance*. Points of difference that are known to have caused misunderstandings are dealt with first.

Many of the airship's principal operational problems are associated with the functions of buoyancy control, of fuel consumption and of interface movements - i.e. landing, mooring, load exchange and take-off. Certain modifications to the basic airship concept have been introduced in recent years which help to some extent in the above areas. An obvious example is vectored thrust - originally used on a number of early airships before World War II and then re-introduced for the Airship Industries Skyship series in the 1980s. Control effectiveness has also been improved, with reduced pilot effort, in experimental ships using fly-by-wire or fly-by-light transmissions in place of direct tension cables. The US Navy's rigid airships of the 1930s also used exhaust water recovery, with some success, to reduce in-flight weight loss owing to fuel consumption, and this technique has also been proposed for modern diesel-powered projects, although such an installation does not yet appear to have flown. In addition to these proven expedients, many other theoretical approaches to buoyancy, fuel consumption and interface problems are constantly being proposed. Many of these are impractical, usually because of the weight penalty involved. Other ideas may have a marginal applicability in particular cases. Such proposals are made repeatedly by different agencies. Chapter 14 on *Improvements*, therefore, sets out to survey briefly, and to evaluate critically, some of the more common of these concepts.

Unconventionality may be attributed to an airship if a major feature of the design is significantly altered from the 'conventional', such as the overall shape, method of lift, source of power, structural configuration, type of lifting gas, or mode of control. These are described in Chapter 15 on *Unconventional Designs* which looks at hybrid (dynastats, rotastats and rotating hull airships), unmanned, hot air, solar and many other designs. A more detailed mathematical analysis is, however, given for the cases of the lenticular and solar-powered airships in Chapters 14 on *Improvements* and 16 on *Solar Power* respectively.

The future of airships rests to a large extent on their economic viability, which is closely related to their unique characteristics, the specific roles that airships are able to fulfil, and on their market potential. These are the considerations examined in Chapter 17 on *Roles and Economic Considerations*. The last Chapter 18 is devoted to *Design Synthesis* of the complete airship which integrates many of the disciplines discussed in earlier chapters - a necessary process for achieving satisfactory design.

2

Basic Principles

E. Mowforth

INTRODUCTION

This chapter deals with some of the basic parameters of airship design and operation under the headings:

- Principles of Aerostatics
- The Aerostatics of the Airship (see also Chapter 8)
- The Aerodynamics of the Airship (see also Chapter 3)
- Unconventional Designs (see also Chapter 15)

Most of these topics will be developed further in later chapters; the objective here is to offer an overview that will help to tie the more detailed treatments together.

PRINCIPLES OF AEROSTATICS

The term 'aerostatics' refers to the static buoyancy of any kind of body immersed in the atmosphere, just as 'hydrostatics' describes the same effect in water. In both cases the upward buoyancy force is equal to the weight of fluid displaced, which in air may be taken as:

$$B = V.\rho_a \tag{2.1}$$

where:

B is the upward buoyancy force acting on the body

V is the volume of the body

ρ_a is the mean density of the local atmosphere surrounding the body

(ρ_a will have a slightly non-linear variation over the height of the body arising from the curvature of the natural atmospheric pressure gradient, but a mean value in Equation 2.1 will be accurate enough for all practical purposes).

This buoyancy force acts on all bodies within the atmosphere but is usually negligible compared with the weight of the body itself; the buoyancy of a human being at sea level, for example, is only about 0.12% of body weight. If, however, the weight W of the body can be made less than that of the displaced air, then there will be a net upward lift L given by:

$$L = B - W \tag{2.2}$$

The obvious case to be considered is that of a balloon incorporating a closed flexible envelope of volume V filled with a gas of density ρ_g which is less than ρ_a, for example hydrogen or helium. The total weight of the system will then be:

$$W = V.\rho_g + W_o \tag{2.3}$$

where: W_o is the weight of the envelope and all its attachments. In any real case the volume of the structure represented by W_o will be so small compared with V that its buoyancy will be negligible, and Equations 1, 2 and 3 may then be combined to give:

$$L_d = V(\rho_a - \rho_g) - W_o = L_g - W_o \tag{2.4}$$

In Equation 2.4, L_d is the 'disposable lift' of the gasbag; this is the lift available for crew, fuel, payload, ballast and supplies when the fixed 'empty' weight W_o has been subtracted from L_g, the 'gross lift' of the gasbag.

The term $(\rho_a - \rho_g)$ represents the gross lift per unit volume, or 'unit lift', of the combination of gas in the envelope and air outside it. At sea level in the International Standard Atmosphere, if the lifting gas is at the same temperature as that of the ambient atmosphere, pure hydrogen for example offers a unit lift of 11.183 N/m^3 (0.0711 lb/ft^3), while pure helium, being twice as dense as hydrogen, generates the slightly lower unit lift of 10.359 N/m^3 (0.0659 lb/ft^3).

The actual mechanism of aerostatic lift is explained in Figure 2.1, which shows a sealed flexible envelope, assumed weightless, containing gas of density ρ_g, at rest in an atmosphere of local mean density ρ_a. The envelope is partially collapsed, its lower surface thus being drawn up into a flat plane on which the inner and outer pressures are equal. (This 'flat' appears at the bottom because the lifting gas is less dense than air; if it were more dense the flat would be at the top).

Starting from this level and working upwards, the internal and external pressures will both fall off with height and rates proportional to the respective densities, so that at a height 'h' above the base the internal pressure will have fallen by ρ_g.h and the external pressure by ρ_a.h. The latter deficit will be greater, so that a differential pressure of $(\rho_a - \rho_g)$h will act outwards across the envelope skin; this wedge-shaped pressure distribution spread over the internal surface of the envelope, will both prevent its collapse and furnish the resultant upward force represented by the 'gross lift' term $V(\rho_a - \rho_g)$ in Equation 2.4. The pressure difference itself is small; at the top of a hydrogen gasbag 30 m (98 ft) high at sea level, for example, it will only reach

335 N/m^2 (7 lb/ft^2), or about 1/300 of atmospheric pressure. With helium the pressure difference would be about 7% smaller.

The gross lift of a gasbag is determined by its volume V and is totally independent of its shape. Free balloons, however, tend to favour a form approaching the spherical, because this offers both the smallest surface area to contain a given volume and the lowest skin tension for a given pressure difference across the skin; both factors facilitate a minimum-weight design.

So long as the gas in the envelope is free to expand - i.e. the envelope is only partially filled - and the gas and air temperatures remain equal, the disposable lift L_d given by Equation 2.4 does not change with altitude. As the gasbag ascends the gas and air densities fall with decreasing pressure but the gas volume V increases in the same ratio. Conversely, falling temperature tends to increase the densities but reduces the volume, so that the two effects again cancel out.

In any 'real' atmosphere the fall in pressure with altitude has a more pronounced effect than the corresponding fall in temperature, so that during ascent the gas will continue to expand until the gasbag is completely filled and no further expansion is possible. The altitude at which this occurs is termed the 'pressure height', because further ascent will cause the differential pressure across the skin of the gasbag to increase; the lift, however, will decrease.

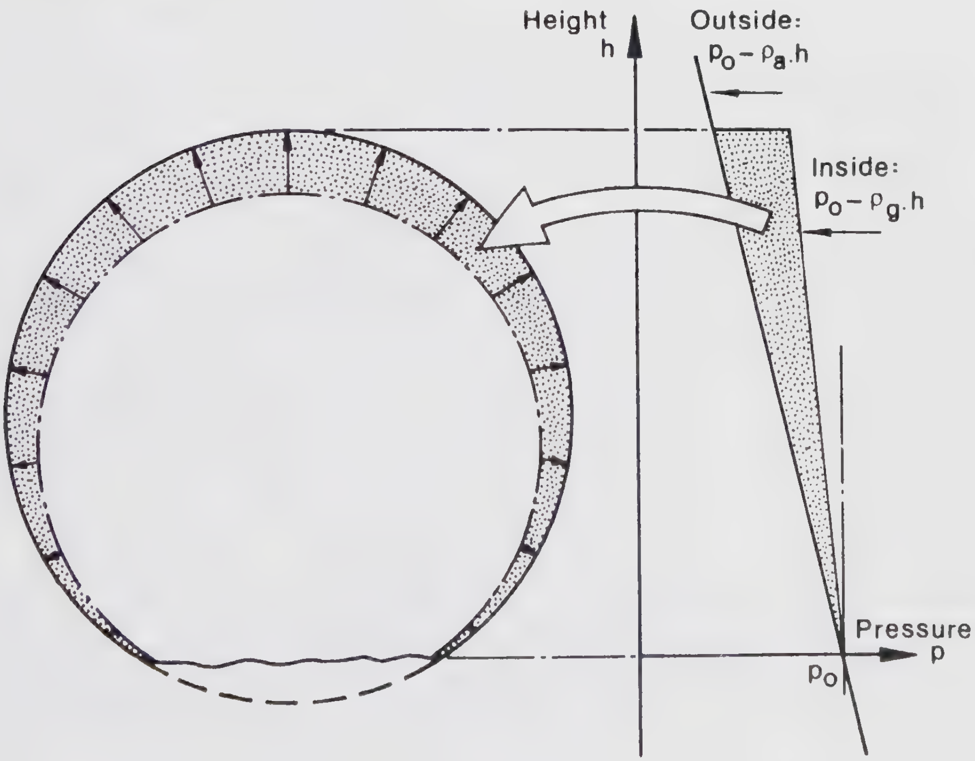


Figure 2.1. The mechanism of aerostatic lift.

In conventional airships and balloons the gasbag skin, for minimum weight, is not designed to carry stresses far in excess of those encountered below the pressure height, which is therefore regarded as an operational ceiling. If this height is exceeded in an emergency, safety valves release gas to protect the envelope against pressure rupture. In recent years, however, high-altitude research has increasingly involved the use of unmanned 'pressure balloons' using envelopes that are strong enough to exceed the pressure height by a significant margin without rupture or gas release. These balloons are so designed that the net lift is positive, causing continuing ascent, above the pressure height; in rising further, however, the net lift falls to become zero at a predetermined equilibrium altitude; which the balloon will then, in theory, maintain indefinitely.

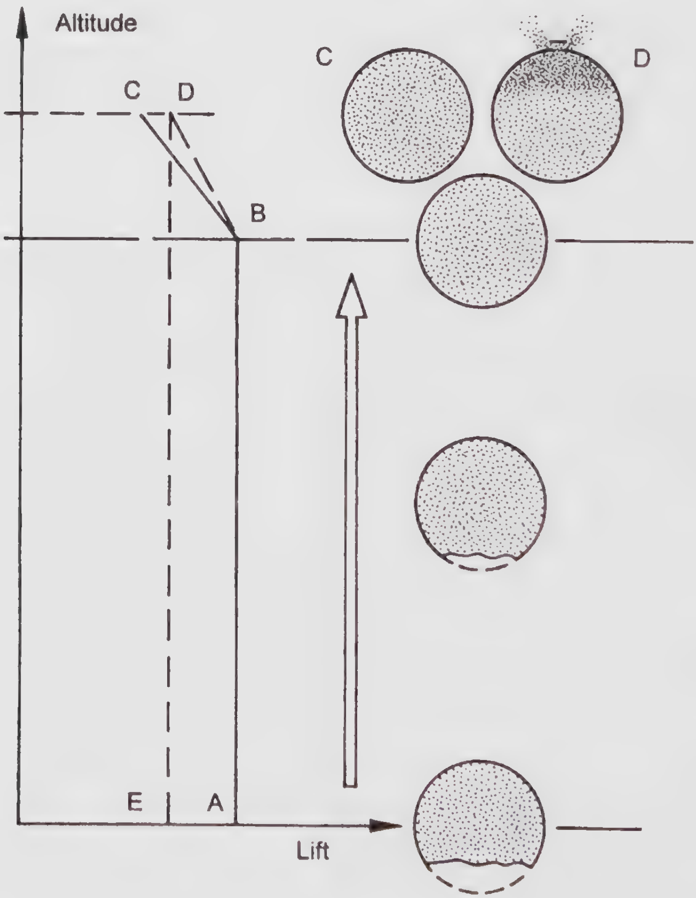


Figure 2.2. Variation of lift with altitude.

These effects of altitude are summarised in Figure 2.2, which shows a partially-filled gasbag leaving sea level at A and climbing with constant lift to the pressure height at B. Temperature equilibrium throughout is again assumed.

If the gasbag ascends beyond B its lift will diminish at a rate depending on whether or not gas is released - as through a safety valve - to prevent a build-up of differential pressure across the skin. If gas is released the lift will fall off to D, which, in effect, becomes the new pressure height for the reduced gas content; subsequent descent will take the gasbag down at constant lift to E. If no gas is released, however, the pressure - and hence the density - of the trapped gas will be higher than it would be if pressure were eased by valving off; lift will consequently be less, taking the ascent up to C rather than D. On subsequent descent the gas pressure will fall, and lift increase, as far as the point B; the lift will then remain constant at its original value back to A.

It follows that, for a given profile of atmospheric pressure and temperature against height, the pressure height will depend upon how much gas is in the gasbag to begin with. This quantity can be defined by an 'inflation fraction' $I = V/V_o$, where V is the effective volume of the contained gas and V_o is the maximum volume of the gasbag itself. A particular value I_o may be assigned to the condition at sea level.

As the air and gas densities are equally affected by pressure and temperature, it follows that:

$$I_o/I = \rho_a/\rho_{ao} \qquad (2.5)$$

and pressure height will then be that at which $I = 1$, i.e. $\rho_a/\rho_{ao} = I_o$. Numerical values can be assigned for a specific density profile, for example that of the hypothetical International Standard Atmosphere (ISA) as a reference base for altitude-related parameters (Table 2.1).

For a given value of I_o the lift will remain constant up to the pressure height, as already explained. For the particular case where the gasbag is full at sea level (I_o = 100%) the gross lift will have its greatest possible value $V_o(\rho_{ao} - \rho_{go}) = L_{go}$, and the disposable lift will also have its maximum value $L_{do} = L_{go} - W_o$. This, however, is a somewhat academic value, because when I_o = 100% the pressure height is at sea level and the gasbag cannot ascend without losing lift. In practice I_o must always be less than 100%, and the disposable lift is then - from Equation 2.4 - $L_d = I_o.L_{go} - W_o$. The ratio of actual to theoretical maximum disposable lift is then:

$$L_d/L_{do} = (I_o.L_{go} - W_o)/(L_g - W_o) \qquad (2.6)$$

In a typical airship the 'empty' weight W_o is about half the gross lift at sea level, L_{go}, so Equation 2.6 becomes $L_d/L_{do} = 2I_o - 1$, and the resulting values are collected in Table 2.1 to show how quickly the disposable lift falls off with increasing pressure height. It follows that balloons and airships operate most effectively at low altitudes.

Table 2.1. *Pressure Height and Disposable Lift (ISA)*

I_o %	Pressure Height		L_d/L_{do} %
	m	ft	
100	0	0	100
90	1085	3555	80
80	2265	7425	60
70	3615	11865	40
60	5010	16440	20
50	6660	21845	0
40	8580	28155	-

Assuming always that gas and air temperatures remain the same, an increase in atmospheric temperature has the effect of increasing the volume of the gasbag whilst decreasing the densities of gas and air in the same ratio; the lift then remains the same but the effective inflation fraction is increased and the pressure height therefore lowered. In the ISA 'tropical maximum' condition, for example, the air temperature is taken to be 30°C above ISA and this increases the low-altitude inflation fraction by about 10%. It follows that to reach a given pressure height in a tropical climate, the initial gas content - and therefore the disposable lift - must be less than for the same pressure height in the ISA. The converse is true in a cold climate; the ISA 'Arctic minimum' (ISA - 30°) causing a fall in inflation fraction of about 10% with a corresponding rise in pressure height.

A different temperature effect is that of 'superheat', in which exposure to direct sunlight, or a rapid ascent into a colder region, causes the gas temperature to rise above that of the surrounding atmosphere. This results in an increase in lift, firstly through the increase in volume and secondly through the decrease in gas density. The former effect predominates; near ISA sea level, for example, a superheat of 10°C will increase the lift of a helium gasbag by 4%, of which 3.5% is due to volume change alone.

An extreme case of deliberate superheat is of course the hot air balloon, which generates its lift by heating an envelope full of air by means of a propane burner at the open neck. For practicable temperatures the unit lift is small compared with helium or hydrogen; at 100°C, for example, hot air generates an ISA sea level lift of 3.1 N/m^3 (0.02 lb/ft^3), i.e. about 28% of that of hydrogen or 30% of the helium figure. Despite this low lift, necessitating relatively large envelopes, hot air has many operational and economic advantages over either gas for sporting balloons and certain types of small airship, in which categories it is now very widely used.

THE AEROSTATICS OF THE AIRSHIP

An airship is fundamentally a balloon with a means of propulsion, but in order to produce an effective vehicle the balloon element has to be considerably modified. The primary requirements of the envelope are now that it should be of streamline form to reduce air resistance and enhance controllability, and that it should be able to sustain the additional loads imposed by aerodynamic forces and propulsive installations. Both these objectives have significant implications for the design of the airship's aerostatic system.

Airships of the classical axisymmetric streamline form fall into two main structural categories, namely 'pressure airships' and 'rigid airships', as shown in Figure 2.3.

In a pressure airship the hull profile is maintained by the pressure of the lifting gas within. In most modern pressure airships there is no additional hard structure to carry the attached accommodation, power plant and installations, and airships of this kind are termed 'non-rigid'. It is also possible, however, to incorporate a long structural keel to share bending loads; in this case the airship becomes 'semi-rigid'. The latter configuration is now rare, as modern materials and techniques allow non-rigid airships - sometimes known as 'blimps' - to reach the large sizes previously attainable only with the additional keel structure.

A rigid airship carries all external loading through a lightweight structural outer shell, traditionally of wire-braced girders with a fabric skin. The shell is divided internally into compartments by a series of wire-braced transverse frames, and each compartment houses a separate gasbag. The lifting-gas pressure now plays no part in maintaining the outer shape and can therefore be much lower than in a pressure airship, thus permitting lighter gasbags. If the ship is large enough the additional weight of hard structure relative to an equivalent pressure ship is more than offset by this reduction in gasbag weight. The effectiveness of the rigid airship therefore increases with size, and this tendency was reflected in the giant rigid airships built between 1900 and 1939, in which year the last full-scale rigid airship - the *Graf Zeppelin II* - was decommissioned. This airship was a sister ship of the preceding *Hindenburg*, which was 245 m (800 ft) long and had a gas capacity of 200 000 m^3 (7 000 000 ft^3).

Pressure and rigid airship principles are combined in the 'metalclad' concept, which essentially involves a pressure airship with a very thin metal skin; this envelope is stabilised against dead weight and aerodynamic loading by internal pressure - like the more usual textile skin - but must in addition incorporate sufficient structural stiffness to prevent collapse on deflation. The small 'ZMC-2' was built on this principle in the US in 1929. It was operational for some years and the concept is frequently advocated for modern projects.

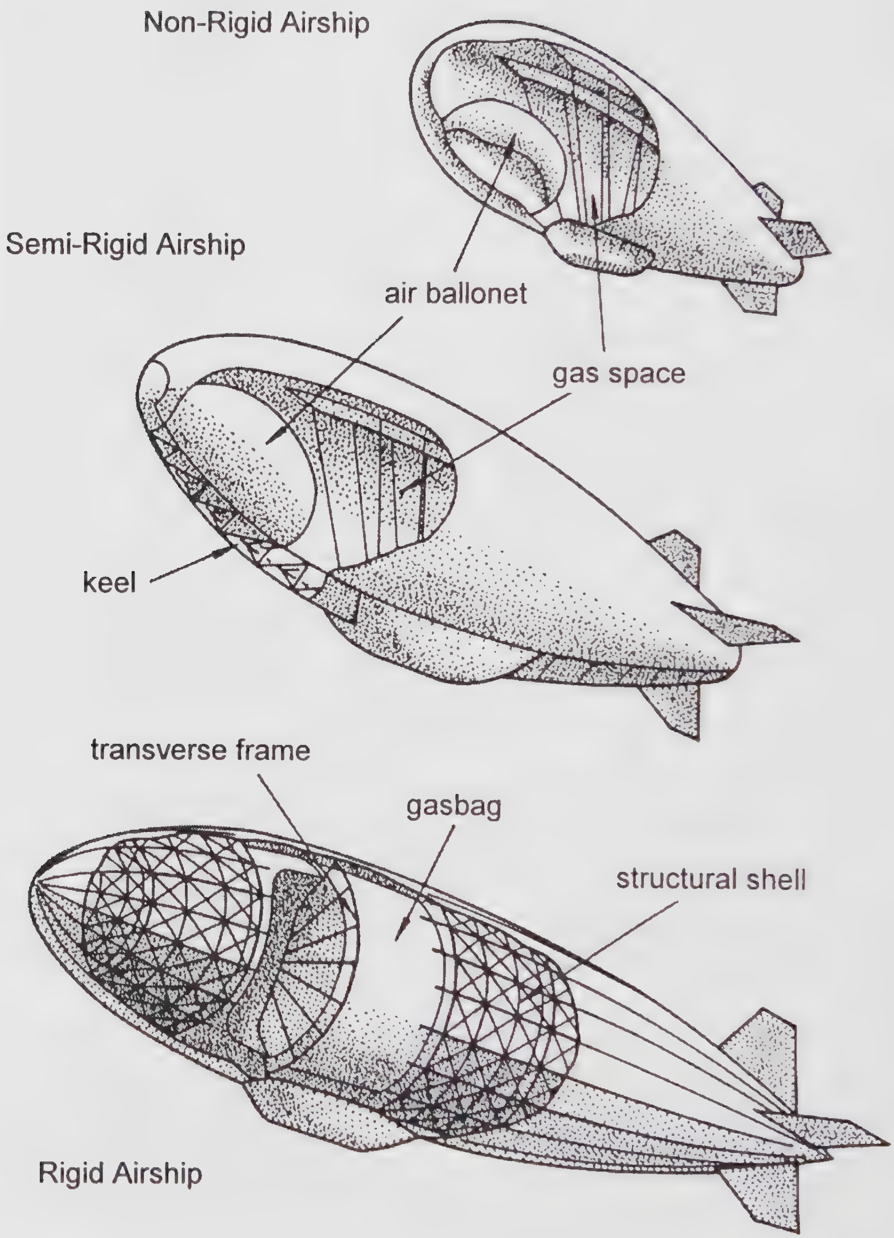


Figure 2.3. Airship structural categories.

We shall now consider the aerostatic characteristics of pressure airships in more detail. The pressure difference across the skin of a pressure airship must be sufficient to maintain the aerodynamic shape of the envelope under all operational conditions of static and aerodynamic loading. This demands a higher differential than is available from the difference between internal and external pressure gradients alone, as was the case in the simple balloon represented in Figure 2.1. At the same time, envelope weight absorbs a large proportion of the gross lift and is a direct function of the differential pressure, which must therefore be first estimated, and then controlled, as accurately as possible to a minimum value for safe operation.

As the aerodynamic forces are proportional to the square of the airspeed, the design pressure differential takes the general form:

$$\Delta p = A + B.V_{max}^2 \tag{2.7}$$

where: A and B are constants for a particular design and V_{max} is the highest airspeed - including gust effects - that the airship is expected to encounter. Typical mid-range figures for a modern non-rigid airship would be:

$$\Delta p = (125 + 0.033V_{max}^2)\ \mathrm{N/m^2} \qquad (V_{max}\ \text{in km/h})$$

$$= (2.6 + 0.0018V_{max}^2)\ \mathrm{lb/ft^2} \qquad (V_{max}\ \text{in mph})$$

The design pressure difference corresponding to a typical V_{max} of 160 km/h (100 mph) would then be about 970 N/m² or 21 lb/ft² i.e. about 1/100 of an atmosphere. The differential would still vary through the depth of the hull by, for example, about 1/600 of an atmosphere for a hull of 15 m (50 ft) deep, owing to the gradient mechanism shown in Figure 2.1.

At any speed greater than about 100 km/h (60 mph) the above differential would not be sufficient to prevent the extreme nose of a flexible envelope from caving in under the purely local stagnation pressure of the impacting airstream. Rather than raise the pressure differential over the whole skin to encounter this isolated pressure peak, the practice is to reinforce the nose with splines to prevent collapse. The skin need then be stressed only for the lower pressure given by Equation 2.7 above, with a consequent saving of skin weight. The nose splines also serve to diffuse the envelope loads transmitted through the nose mooring attachment.

Since the envelope is only designed to carry the above differential pressure with a small reserve factor, it is necessary to keep the differential constant within close limits despite the effects of varying temperature and pressure; this is achieved through the ballonet system shown in Figure 2.4.

Air ballonets - usually two in number - are installed within the gas space and connected to an external air supply pressurised to the required differential above atmospheric. When fully distended the ballonets may occupy as much as 40% of the envelope volume but within the altitude range for normal operation they are partially collapsed and hence free to change their volume. This change occurs spontaneously to equalise pressures across the ballonet skin, thereby transmitting the controlled air pressure to the lifting gas regardless of external conditions. The ballonet volume will fall with decreasing atmospheric pressure and rise with decreasing temperature; for an ascending airship the former effect will far outweigh the latter in any 'real' atmosphere, causing the ballonets to shrink as the airship climbs and expand with descent. Superheat will reduce the ballonet volume.

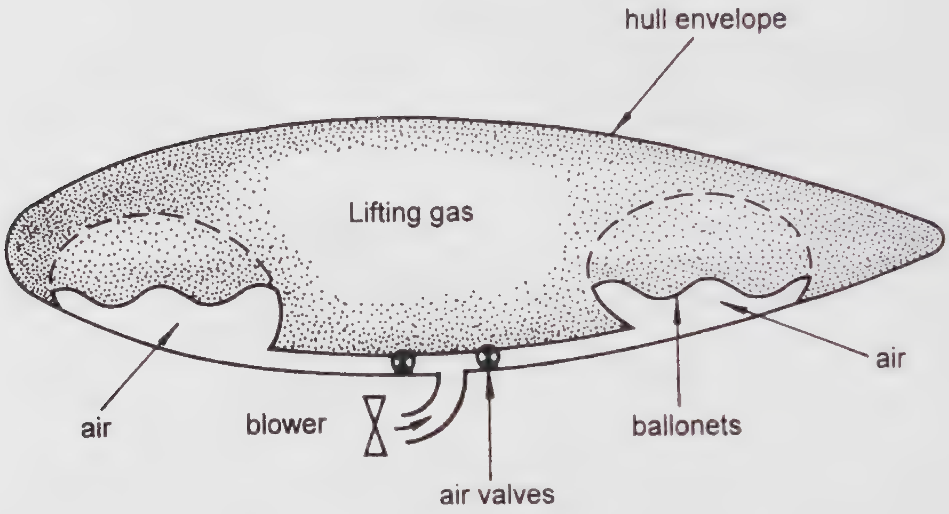


Figure 2.4. Pressure control system in a pressure airship.

The control pressure is traditionally generated by airscoops pointing into the propeller slipstream and leading into the ballonets through control valves and ducts; separate blowers, however, are used on some modern airships. Valves also permit differential inflation of the front and rear ballonets to offer some control of the position of the centre of buoyancy.

The pressures throughout the system are - in any practical case - so close to atmospheric that the airship's gas space is effectively behaving like the expandable gasbag in open atmosphere analysed earlier, and the parameters of Table 2.1 are still applicable. If, for example, an airship has ballonets capable of occupying up to 40% of the hull volume and these are fully distended at ISA Sea Level, the effective inflation fraction I_0 is 60% and the pressure height 5010 m (16 440 ft), while the disposable lift is reduced by 80% - compared with the value if the ballonets were exhausted at sea level (I_0 = 100%). The pressure height for a pressure airship becomes the altitude at which all the air has been ejected from the ballonets so that no further expansion of the gas space can be accomplished. Protection by safety valves is necessary for ascent beyond this point.

The low value of differential pressure also calls for careful design of the suspension system in order to prevent excessive distortion of the envelope by the dead weight of the gondola and installations. The system originated by Goodyear in the 1920s, and still used on most modern non-rigid airships, is shown in Figure 2.5; the suspended load is shared between an internal catenary system, comprising an array of cables attached to the upper skin through stress-diffusing textile curtains, and an external catenary diaphragm, which distributes the stresses of the gondola attachment over an increased perimeter of skin. In some modern airships the external catenary is omitted and the gondola is connected directly to the envelope.

Buoyancy control - i.e. the regulation of the excess or deficit of aerostatic lift relative to the neutral condition - is in one respect less difficult in an airship than in a balloon; the moving airship can generate a vertical aerodynamic force by tilting the nose up or down, and thereby balance a significant discrepancy between aerostatic lift and dead weight. This facility, however, disappears as the airship slows to a hovering mode. An additional factor - not present in a free balloon - is the progressive loss in weight as fuel is consumed in flight. The classical technique of dropping ballast in order to reduce weight is still applicable but gas cannot be released to reduce lift - except in cases of emergency - because of the high cost of the helium with which modern airships are filled (in order to avoid the fire risk inherent in the use of hydrogen).

Two other techniques have been used to control the buoyancy of an airship directly. The first, rather uncertain but effective when available, depends on the collection and storage of rainwater and condensation from the hull skin. The second, more reliable but involving weight and complexity, involves the condensation and collection of water from the engine exhausts; combustion of a hydrocarbon fuel in air can theoretically generate a weight of water greater than that of the original fuel. Systems have been devised on this basis with the aim of compensating for the weight of fuel burnt, although total balance is difficult to achieve in practice. The technique can only be used effectively with piston engines (petrol or diesel); gas turbines have a lower exhaust water content, a higher exhaust temperature and a greater sensitivity to back-pressure, all militating against any practicable condenser system. Exhaust water condensation was used in US rigid airships in the 1920s and 30s and has been proposed for the diesel-powered non-rigid YEZ-2A of Westinghouse Airships Inc.

Another approach is to balance the excess of static lift or weight by an externally applied vertical force. One way of doing this is by operating ‘heavy’, i.e. by retaining an excess of weight over static lift at all times and making up this imbalance by dynamic lift in forward flight. Hovering is not then practicable, and take-off and landing require a ground run like that of a conventional aeroplane. This technique is used by most of the non-rigid airships currently in operation. Another method, used on some modern airships, involves swivelling the propellers about a lateral axis to furnish a vertical thrust component. This system, known as ‘vectored thrust’, permits power-on hovering and greatly facilitates low-speed manoeuvres but does, of course, imply additional weight and complexity. The system was used on all the Airship Industries *Skyship* 500 and 600 series and also on the gas turbine-powered Loral Goodyear GZ-22.

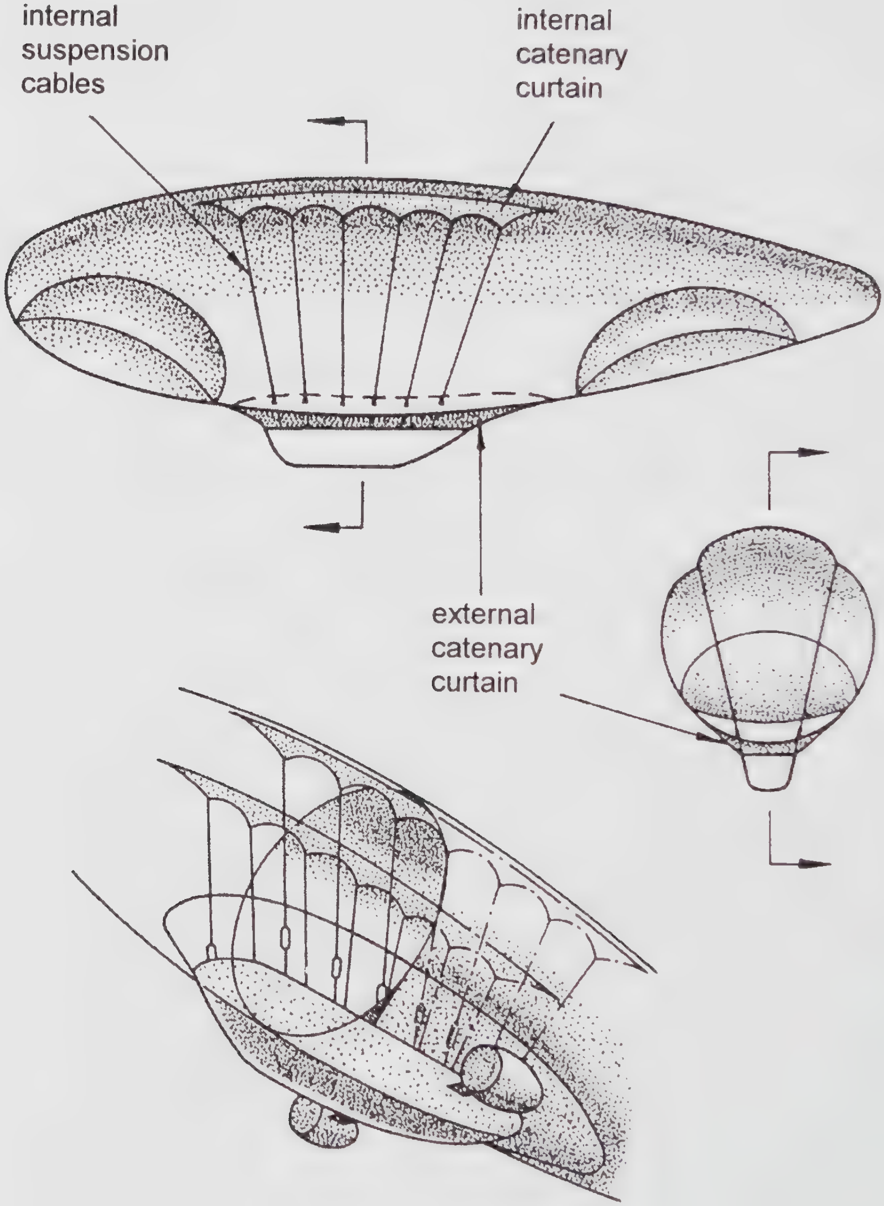


Figure 2.5. Non-rigid airship suspension system.

A third principle, used successfully on the *Graf Zeppelin* (1928-37), is to avoid weight loss through fuel consumption altogether by burning gaseous fuel of the same density as air. The fuel used in the *Graf Zeppelin* was 'Blaugas', a propane derivative. Proposals have been made more recently for burning a 'constant-weight' combination of liquid fuel and natural gas but the system has not yet been tried. Many other schemes for buoyancy control have been proposed, all essentially impracticable on the grounds of weight, safety or controllability.

THE AERODYNAMICS OF THE AIRSHIP

The aerodynamic performance of the airship will be covered at some length in Chapter 3 but it is convenient to summarise here some of the salient characteristics, in order to explain certain aspects of airship design and operation.

The airship is essentially a low-speed vehicle; airships have mostly flown below 160 km/h (100 mph), and an upper limit of 130 - 150 km/h (80 - 95 mph) - depending on the role - is generally considered appropriate. Higher speeds generate a rapid escalation of weight and fuel consumption; structure weight increases to meet the higher aerodynamic loading, power plant weight increases with output - the power requirement is roughly proportional to the cube of the airspeed - and the fuel required to cover a given still-air distance varies with the square of the speed. Despite elegant streamlining, aerodynamic drag is high; the drag of the hull by itself is usually less than that due to the attached gondola and installations, which interfere with the flow over the envelope as well as contributing their own drag components.

The bare hull of classic streamline form is directionally unstable, tending always to turn broadside on to the direction of motion. In the horizontal plane this deviation is resisted by fixed vertical tailfins; if large enough these will confer weathercock stability but, in the interests of controllability and structure weight, the fins are usually made slightly too small to attain this effect. The airship, if left alone, will then tend to drift into a large circular path, readily corrected by occasional small movements of the rudders hinged to the vertical fins. In the vertical plane there is a corresponding tendency towards uncontrolled climb or descent, inhibited, however, by the pendulum effect of suspended installations and further reduced by horizontal tailfins. These also may be undersized, leaving the airship with a residual aptitude to raise or lower the nose gently. This trend again is corrected by intermittent adjustment of the elevators hinged to the trailing edges of the horizontal fins. Typical tail arrangements are shown in Figure 2.6.

In deliberate manoeuvres the rudders are used for turning and the elevators to tilt the hull axis, either for climb and descent or in order to counteract any buoyancy imbalance through dynamic lift. The hull and fins of a conventional airship constitute a somewhat inefficient lifting body that can 'stall' if the angle of attack, i.e. the nose-up angle of the hull axis relative to the flight path, exceeds a critical value; the dynamic lift available is therefore limited. The lift varies with the angle of attack and the square of the speed, so that a 'heavy' airship may be close to the stall when flying slowly during take-off or landing. To obtain the necessary 'nose-up' ground clearance for these events the lower vertical fin may be made smaller than the upper one; alternatively the fins may be arranged in a diagonal 'X' or an inverted 'Y' configuration, requiring co-ordinated movements of all the control surfaces to induce the turn, climb or descent. Control operation in most airships is manual and response is sluggish, requiring large control movements with considerable anticipation. In some modern types the pilot effort may be reduced by servo actuators using signals transmitted electrically ('fly-by-wire') or through optic fibres ('fly-by-light'), but these techniques are still largely experimental.

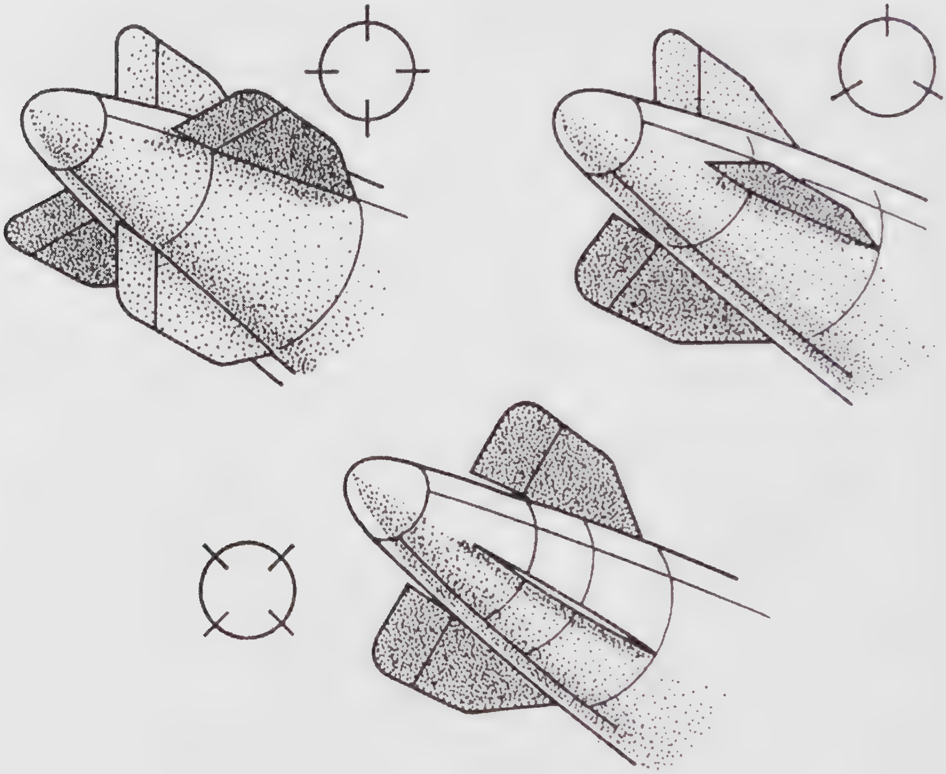


Figure 2.6. Control surface arrangements.

The classical streamline hull shape - an axisymmetrical elongated teardrop - remains an ideal compromise between structural and aerodynamic requirements as far as in-flight motion is concerned; this shape, however, presents considerable problems in ground handling, the techniques of which are described in detail in Chapter 11. Mooring is usually effected by coupling the extreme nose to a fixed mast and ballasting the ship to keep a single castoring wheel (under the gondola) in contact with the ground. The ship may then 'weathercock' spontaneously around the mast as the wind direction changes. The problems of this procedure arise in getting the airship on to the mast in the first place and in withstanding the effects of gusting, which can cause severe oscillatory forces to be transmitted through the mast.

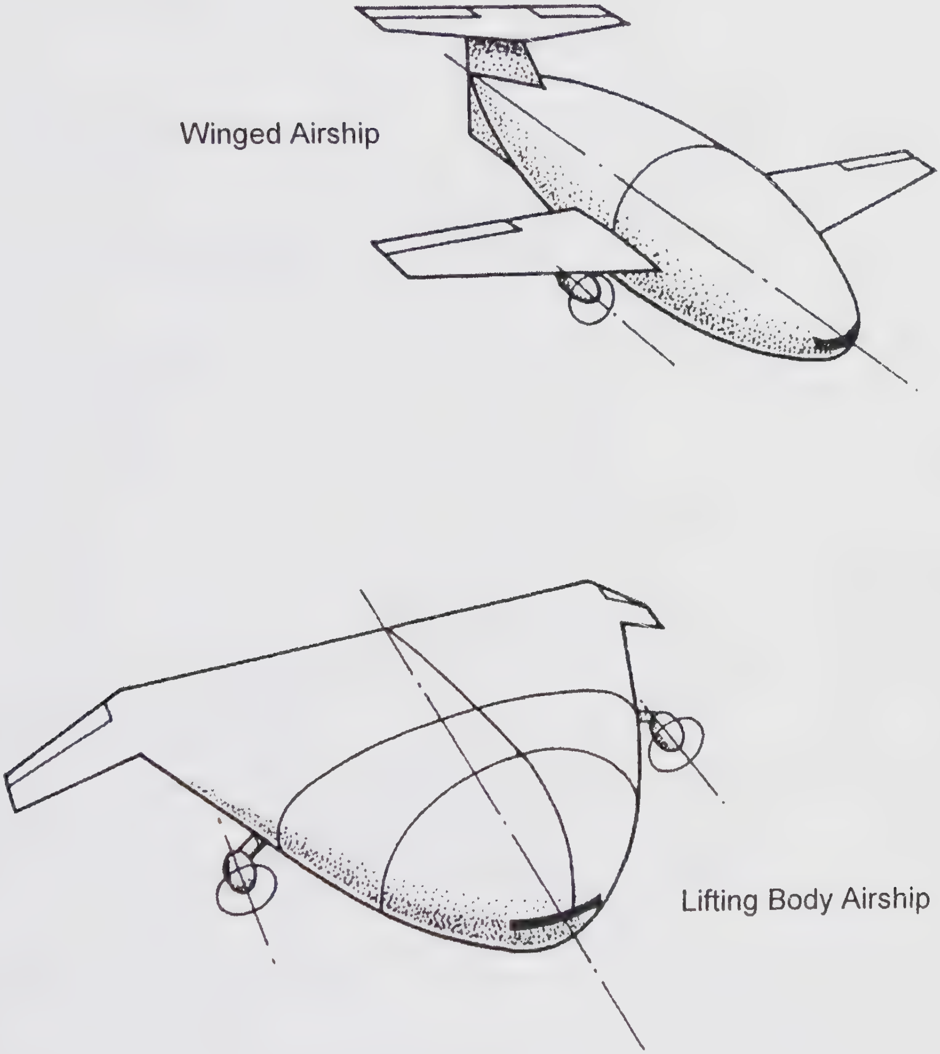


Figure 2.7. Winged and lifting body airship concepts.

UNCONVENTIONAL DESIGNS

Airships currently in commercial operation are normally of the classical streamline form described above, differing only in technical detail from the non-rigid designs developed in the 1930s. Various alternative configurations have been proposed with the aim of making the concept more flexible in operation, or of adapting it to certain specialised applications.

These new approaches fall broadly into two categories, both derived through extrapolation of existing configurations. They have led to 'hybrid' layouts combining the characteristics of the classical airship with those of either an aeroplane or a helicopter; both arrangements dispense with the use of ballast and would greatly facilitate ground handling and load exchange.

The first combination seeks to enhance the aerodynamic lift capacity of the conventional airship by adding wings or by developing the hull geometry into a more efficient lifting body. The airship would thus, like an aeroplane, be able to carry a significant proportion of its payload through dynamic lift. The 'winged' and 'lifting body' options are shown in their simplest form in Figure 2.7. The resulting aircraft would need to operate with a ground run for take-off and landing but could use much smaller spaces than would be required by an aeroplane to carry the same load. Further, their configuration would make the operations of safe ground handling far less complex than for a conventional airship.

Project studies offered in this category during the 1970s included the Ames *Megalifter* and the Aereon *Dynairship*, sketched in Figure 2.8.

The *Megalifter* incorporated a soft envelope containing 200 000 m^3 (7 000 000 ft^3) of helium surrounding a large cargo bay. Conventional wings carried propeller turbines or turbofans offering a cruising speed of 330 km/h (205 mph). Maximum payload and range were to be respectively 180 tonne and 16 000 km (10 000 miles); span and length would be respectively 162 m (530 ft) and 198 m (650 ft).

The *Dynairship* used its profiled deltoid hull as the lifting agent. A range of vehicles was proposed, the largest to be 183 m (600 ft) long and to carry a maximum payload of 1000 tonne. It was anticipated that such an aircraft would be able to deliver 340 tonne across the Atlantic at 200 km/h (125 mph).

A popular lifting body concept is the lenticular hull or 'flying saucer' explored by various agencies; the structural and aerodynamic characteristics of this geometry have, however, proved difficult.

The *Megalifter* did not develop beyond the drawing board. A small manned vehicle to demonstrate the *Dynairship* geometry was successfully flown in 1971 but nothing ensued. Thermo-Skyships flew a model 'saucer' in 1975 and a Mexican 6-seat lenticular airship of diameter 32 m (105 ft) - the MLA-32-A - flew briefly in 1988.

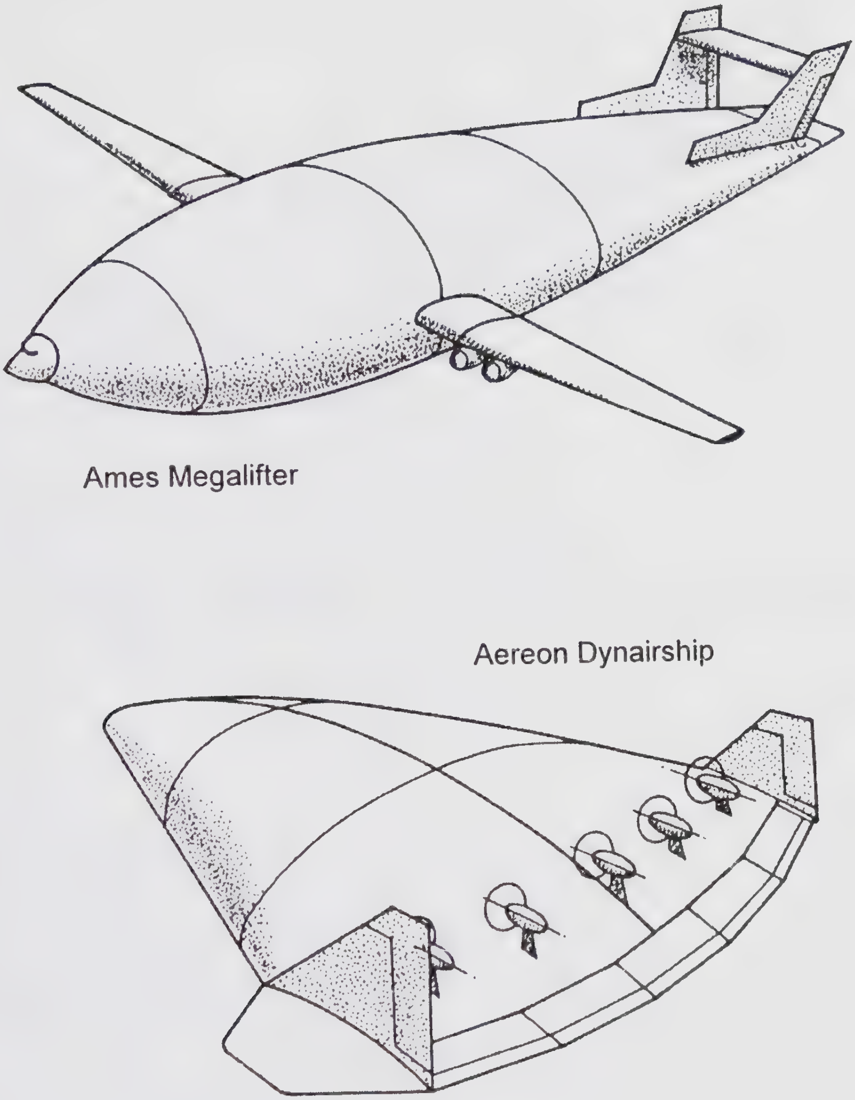


Figure 2.8. Winged and lifting body projects.

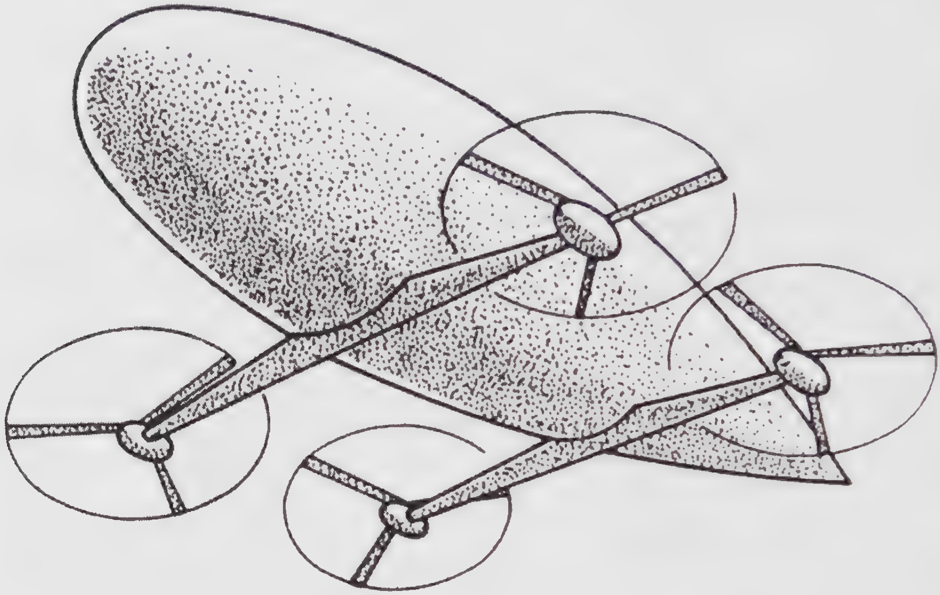


Figure 2.9. Airship with lifting rotors.

Figure 2.9 illustrates the principle of the second form of hybrid airship mentioned above (*viz.* the hybrid airship-helicopter); the vectored thrust used for buoyancy adjustment in some modern airships has been taken a logical step further to become a rotor system carrying most or all of the payload. Such a hybrid may also be regarded as an aerostatically-enhanced helicopter: if the dead weight of the unloaded helicopter - normally carried by rotor lift - is sustained instead by aerostatic lift, the whole of the rotor's lifting capacity is released for payload and control.

Various studies based on this principle have been pursued. The Piasecki *Heli-Stat* was first proposed in 1974 and completed in prototype form - after many delays - in 1986. This first aircraft - sketched in Figure 2.10 - was primarily a demonstration vehicle only; it embodied many existing units, the main components being an old US Navy ZPG-2 envelope of length 105 m (343 ft) and capacity 28 000 m^3 (1 000 000 ft^3) and four ex-Navy Sikorsky H-34 helicopters. The tail rotors of the helicopters were to be replaced by axial thrust propellers for forward propulsion; the total rotor lift of the system was expected to be 25 tonne. The machine was accidentally destroyed during early trials.

Other unusual configurations have been offered from time to time; notable among them the All American Engineering Corporation's *Aerocrane* of 1974, which was tested in model form; the complicated Aerolift Inc *Cyclocrane*, flown as a demonstrator vehicle in 1984; and the Magnus Aerospace Corporation's project, using the Magnus lift of a rotating sphere, which was tested in model form in 1981.

Further information on unconventional airship designs is given in Chapter 15.

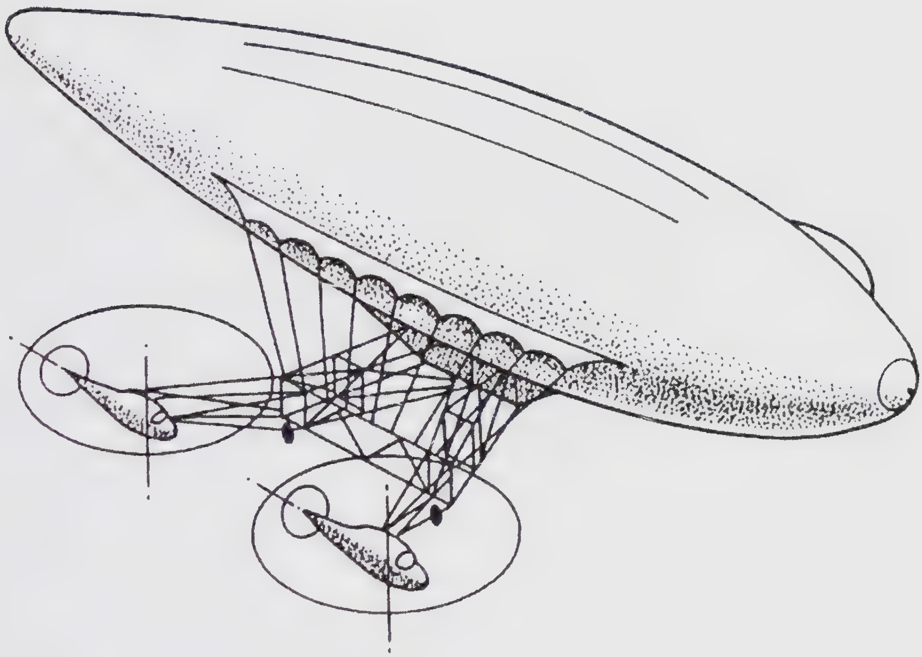


Figure 2.10. The Piasecki Heli-Stat.

Aerodynamics

I. Cheeseman

BASIC ASSUMPTIONS

Aerodynamic forces occur when a body moves relative to the air in which it is immersed. These forces are classified as steady when they are invariant with time, or transient when they are not. The steady forces arise, for example, when a body is in uniform motion in a still atmosphere. Transient forces occur during manoeuvres or owing to turbulence in the atmosphere. Aerodynamic forces and moments arise from the local surface pressures, which, when integrated over the whole body, give the overall forces and moments. It is therefore necessary to determine the local pressures.

The force on a very small area δA of a body is given by the product of the static pressure p_S and δA. The application of Newton's Laws to the motion of a fluid leads to Bernoulli's equation. For a non-viscous, incompressible fluid in steady motion this takes the form:

$$p_s + 0.5\,\rho\,V_s^2 = p_a + 0.5\,\rho\,V^2 \tag{3.1}$$

where:

p_s = the local static pressure

V_s = the local velocity at point under investigation

p_a = the static pressure

V = velocity of the fluid far removed from the body

ρ = the density of the fluid everywhere

From Equation 3.1 it is clear that if $V_s > V$ then $p_s < p_a$. The force on the small area around this point, relative to that which acts when the body is at rest and the local static pressure is p_a, is $(p_s-p_a)\delta A$, which is negative and therefore acting normally outwards. Non-dimensional pressure coefficients allow comparison between different flow conditions and/or shaped bodies. The non-dimensional pressure coefficient is defined as:

$$C_p = (p_s-p_a)/0.5\,\rho\,V^2 \tag{3.2}$$

C_p has the value 1.0 when $V_s = 0$, i.e. the flow is brought to rest on the surface. It becomes negative when $V_s > V$. An example of the pressure distribution around a circular cylinder is shown in Figure 3.1 curve A. From the symmetry of the pressure distribution over the front, from 270° to +90° and the rear, 90° and 270°, it is clear that there will be no net force in the direction of the free stream, i.e. no drag force. The reason for this ideal, and not realisable, result is that viscous forces have been neglected.

Air has a very low viscosity; at 300 °K it is 18.325 x 10^{-6} but that for water is 1.0 x 10^{-3} Nsm^{-2}. Nevertheless the value for air is sufficient to produce a shearing action in the flow along the surface of a body. The air in immediate contact with the body is at rest relative to the body. In laminar flow consecutive layers of air move parallel to the surface at increasing speeds until the inviscid solution speed is attained. However, this orderly arrangement eventually breaks down and the flow becomes turbulent. Eddies are produced which entrain fluid from the free stream and mix it with the sluggish air already there. This region of lower velocity air in both laminar and turbulent flow is called the boundary layer. The loss of air velocity in the boundary layer results in a loss of momentum and hence a drag force, which is naturally called **skin friction drag**.

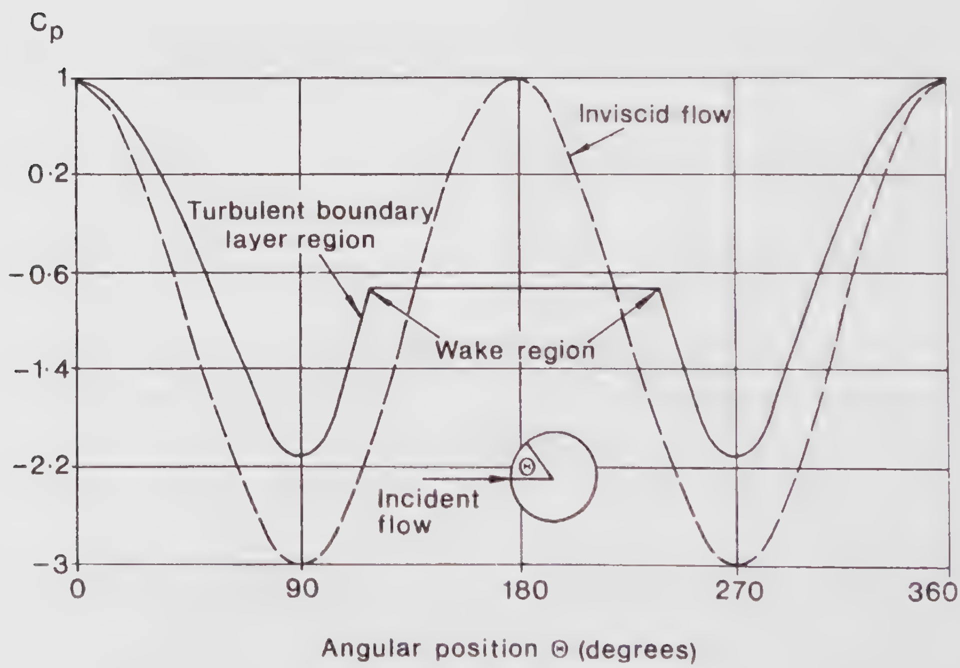


Figure 3.1. Pressure distribution around a circular cylinder.

The development of a boundary layer is affected by the pressure on the body. Figure 3.1 shows that the static pressure decreases over the nose region 0^o to 90^o. This pressure gradient accelerates all the fluid including the boundary layer. The thickness of the boundary layer therefore grows more slowly. However, in the region 90^o to 180^o the opposite effect is observed resulting in a deceleration of the fluid. The fluid close to the surface already has a low velocity and this deceleration causes it to move in the opposite direction to the local free stream. When the net local velocity in the inner boundary layer becomes zero, conservation laws mean that the fluid moves outwards from the surface. The boundary layer therefore separates from the surface and a wake is formed (Figure 3.1, continuous curve). The static pressure on the surface of the body within the wake is no longer governed by the ideal local velocity but remains roughly constant at the value where the boundary layer separated. The symmetry of the pressure distribution over the front and rear of the body is destroyed and a drag force results. This contribution is called **form (or pressure) drag.**

Form drag can be altered by streamlining the shape of the rear of the body. The shape is chosen to reduce the rate at which the local static pressure rises in this region.

Aerodynamic lift is the component of pressure normal to the free stream. Total lift is obtained by integrating this component over the whole body. For both curves in Figure 3.1, the symmetry of the upper and lower surface pressure distributions results in zero net lift. To produce lift the local flow velocities must be greater over the upper than over the lower surface of the body so giving rise to different static pressure distributions. Such a difference in pressures is usually produced by flying the body at an angle to the free stream. This change in pressure distribution affects the boundary layer development and hence the drag components discussed above.

The preceding discussion assumed that the pressure distributions measured in the direction of the free stream were identical for all stations at right angles to it (chordwise and spanwise for an aircraft wing). All real lifting bodies are finite. At the 'spanwise' limits of a lifting body the pressure difference between upper and lower surfaces cannot be supported and air flows from the lower to the upper surface. This results in a trailing vortex pattern; an example being the vapour trails of high flying aircraft. The trailing vorticity produces a velocity on the body normal to the free stream which tilts the incident flow slightly downwards. The lift vector, which is normal to the incident flow, tilts backward by the same amount. Resolving the lift force along and normal to the true free stream produces a component force in the drag direction. This is called the **induced drag** because it is induced by the production of lift on a finite size body. Typical airship hulls experience all of these effects. It will be readily appreciated that the three-dimensional flow around such a body, when it is inclined at an angle to the incident flow, can result in a complex shed vortex wake and associated cross flows on the body.

The above discussion has concentrated on forces on a body but the local pressure forces produce moments about reference axes which play a major role in determining the control requirements of a flying vehicle. These will be discussed further as the need arises.

DRAG

A given lift is produced by an aircraft wing which has a much smaller volume than an airship. However, the wing has to be in forward motion to develop lift. Drag is therefore of primary importance.

The Bare Hull

It is advantageous to express all aerodynamic forces and moments on a body in non-dimensional form. Aerodynamic forces are divided by the dynamic head of the incident flow V and a reference area A. Thus the lift C_L and the drag C_D coefficients are expressed as:

$$C_L = \text{Lift}/(0.5\ \rho\ V^2\ A) \qquad C_D = \text{Drag}/(0.5\ \rho\ V^2\ A)$$

In these two expressions only A is not unambiguously defined. The lift of an aircraft is produced almost entirely by the wing so the relevant area A is the wing plan area. The lift of a buoyant craft is related directly to its volume so A is often chosen to be (Buoyant Volume)$^{2/3}$ However, owing to the large surface area of buoyant craft, skin friction is the largest fraction of the total drag. For this reason many reports use force coefficients in which A is the surface area. Care must always be taken when comparing non-dimensional coefficients taken from different publications to check that the same variables have been used.

It is possible to determine a conversion factor between the two non-dimensional forms for a particular class of shapes. For bodies of revolution of length l, maximum diameter d and with a fixed volume:

$$d^2.l = \text{constant}$$

Young (1939) calculated for bodies based on the R101 shape the variation of A/l^2 as a function of d/l (The ratio l/d is the Fineness Ratio of a body. Using the ratio d/l, however, produces simpler approximate formulae for drag and the like. The ratio d/l is the Thickness Ratio. Although d/l is a ratio it will be expressed by the value of d as a decimal of l). The result, for $0 < d/l < 0.35$, is almost the straight line:

$$A/l^2 = 2.33.d/l$$

Young also showed that the volume satisfied the relation:

$$Vol/l^3 = 0.465.(d/l)^2$$

If C_{DV} and C_{DA} are the drag coefficients of a particular body made non-dimensional by (vol)$^{2/3}$ and surface area A respectively, then:

$$C_{DV}/C_{DA} = A/(Vol)^{2/3} = 3.88.(l/d)^{1/3} \qquad (3.3)$$

This relation was checked using data for Skyship 500 given by Reid (1987). The dimensions are:

$$\begin{aligned} Vol &= 5131m^3 \\ A &= 1782.92m^2 \\ l &= 50m \\ d &= 14m \end{aligned}$$

Thus $A/(Vol)^{2/3} = 5.976$ and $3.88.(l/d)^{1/3} = 5.928$, which represents an error of 0.8%. Equation 3.3 is therefore sufficiently accurate to convert between the two non-dimensional systems.

Minimum skin friction drag will result from a minimum surface area for a given surface finish. The minimum surface area for a given volume is a sphere. While this has some structural advantages, it has a high drag in forward motion owing to its large form drag. Changing the shape to a body of revolution about an axis along the flight direction reduces the form drag. There are structural reasons for keeping the shape axisymmetric about the line of flight. The variation of drag as the thickness ratio, d/l, is varied was examined by Young. Using experimentally derived pressure distributions he calculated the contributions due to skin friction and form drag. Comparing the bodies on the basis of equal volume, and hence equal hydrostatic lift, he derived Table 3.1.

Table 3.1. *Variation of drag of bodies of revolution of constant volume with thickness ratio*

d/l	A/l^2	Reynold's No. x 10^7	C_{DA}	C_{DV}
0.05	0.114	2.360	0.00271	0.0285
0.10	0.229	1.491	0.00301	0.0251
0.15	0.342	1.138	0.00329	0.0240
0.182	0.413	1.000	0.00347	0.0237
0.20	0.456	0.940	0.00356	0.0236
0.25	0.570	0.810	0.00386	0.0237
0.30	0.692	0.716	0.00422	0.0244

The final column for C_{DV} has been produced from his values of C_{DA} by using Equation 3.3. Comparing the values of C_{DA} and C_{DV} it is seen that C_{DA} increases monotonically with d/l whereas C_{DV} has a minimum. Young suggests that this occurs for d/l = 0.182 while the more approximate values in column 5 of Table 3.1 suggest d/l = 0.2. The minimum is clearly very flat and Skyship SK600 with d/l = 0.258 would only incur a small drag penalty compared with the 'optimum'. It must be remembered that low drag is only one factor in optimising a design, for example the increase in thickness ratio can reduce structural bending moments. This could lead to lower structure weight which could more than offset the increase in drag and resulting fuel load.

Young investigated the sensitivity of his results to variation of some important parameters. Small changes in shape of bodies of revolution with the same thickness ratio may result in appreciable changes in surface area. Total drag, however, was little affected.

Variation of local skin friction coefficient C_f with the position of the transition from a laminar to a turbulent boundary layer and with Reynolds number Re was examined. For a body with thickness ratio = 0.169 and Re = 10^8 - the latter corresponding to the Airship Industries SK600 flying at 31 m/s - Figure 3.2a shows $C_f\ 2\pi r/l$ vs. distance from the nose x for three transition points. The total skin friction drag coefficient C_f is obtained by integrating the area under curve A from x = 0 to the point where curves B, C and D start and then adding the area under each of them. Figure 3.2b shows C_f and the total drag coefficient C_a against transition point position. The skin friction contribution to the total drag is clear.

Young repeated the calculations for bodies with different thickness ratios, the results are shown in Figure 3.3. Since C_f/C_a varies little with transition point position at a given thickness ratio, Young suggested the following straight line approximations to the mean value at each thickness ratio was adequate for simple performance estimates:

$$\frac{\text{Skin Friction Drag}}{\text{Total Drag}} = 0.6\ d/l \qquad \frac{\text{Form Drag}}{\text{Total Drag}} = 1 - 0.6\ d/l \qquad (3.4)$$

Reynolds number (discussed later in the section on ***Computational Fluid Dynamics***) plays a major role in determining the aerodynamic performance of a body. Young showed that at Re = 10^7, appropriate to an airship smaller than the SK600 and travelling more slowly, the drag coefficient would be increased by about 55% relative to that at Re = 10^8. The drag coefficient continues to fall as Re increases beyond 10^8.

If the boundary layer separates from the surface appreciably ahead of the tail then the form drag will be increased and Equation 3.4 will be inappropriate. Young quotes the wind tunnel results of Ower and Hutton (1929) who found no evidence of separation on a body with thickness ratio 0.33, which is just outside the range shown in Figure 3.3.

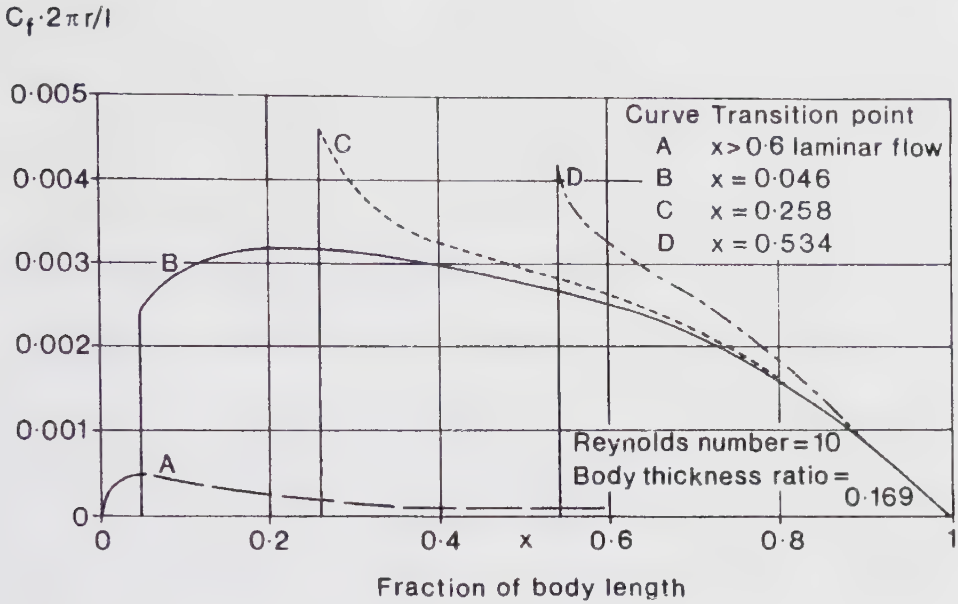


Figure 3.2a. Local skin friction distribution.

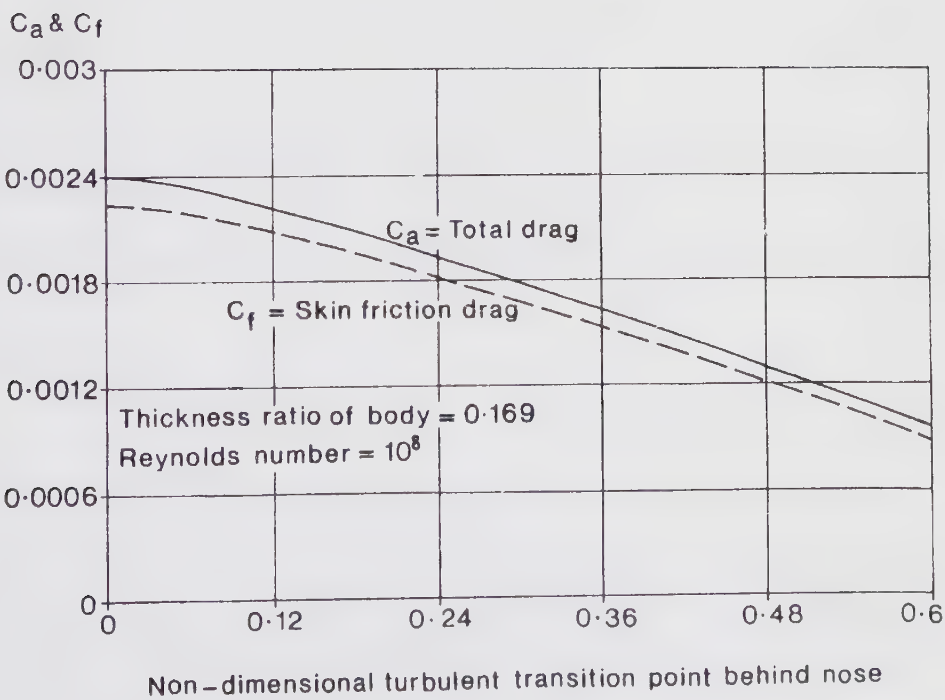


Figure 3.2b. Variation of total & skin friction drag with transition point position.

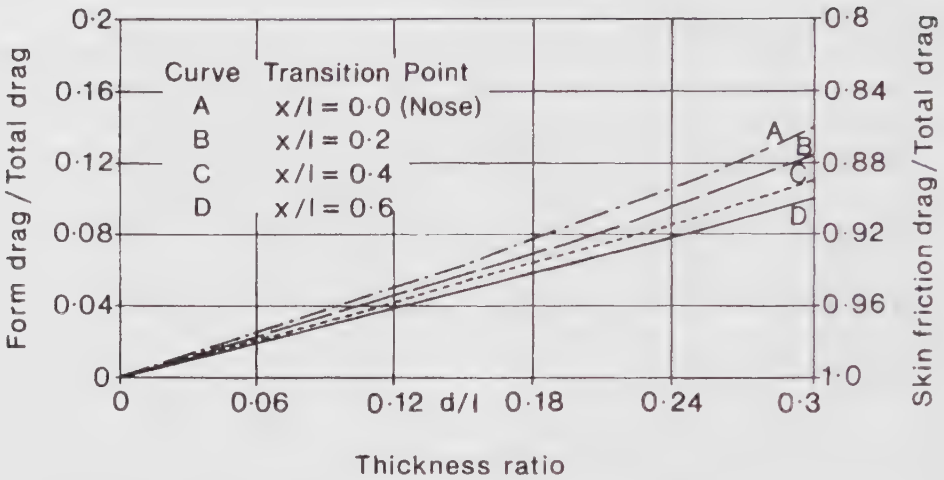


Figure 3.3. Variation of form & skin friction drag with thickness ratio.

Hoerner (1957) analysed experimental data and compared them with theory to produce empirical formulae which may be used to assess the drag of bodies. In his section 6c he deals with the drag of streamline bodies. For most airships the flow over the hull is turbulent and for these conditions it was deduced that:

$$C_{DV}/C_f = 4(l/d)^{1/3} + 6(d/l)^{1.2} + 24(d/l)^{2.7} \qquad (3.5)$$

Equation 3.5 has a minimum value when the thickness ratio $d/l = 0.217$. This is greater than Young's figure of 0.182 but both curves are very flat in the region of the minimum.

Hoerner suggests that C_f for practical levels of surface roughness and for $Re > 5 \times 10^6$ varies as:

$$C_f = 0.043/Re^{1/6} \qquad (3.6)$$

Combining Equations 3.5 and 3.6 gives:

$$C_{DV} = \{0.172(l/d)^{1/3} + 0.252(d/l)^{1.2} + 1.032(d/l)^{2.7}\}/Re^{1/6} \qquad (3.7)$$

C_{DV} has been calculated using Equation 3.7 for the values of d/l in Table 3.1 and the results, together with those by Young, shown in Table 3.2. Young's work is largely theoretical while Hoerner uses mainly experimental evidence; the agreement is thus acceptable.

Table 3.2. *Values of C_{DV} given by Young and by Hoerner for typical airship hulls*

d/l → $C_{DV} \times 10^2$ ↓	0.05	0.10	0.15	0.182	0.20	0.25	0.30
Young	2.85	2.51	2.40	2.37	2.36	2.37	2.44
Hoerner	2.78	2.46	2.36	2.35	2.35	2.42	2.55

The National Physical Laboratory in England suggested a low drag shape for an airship hull. A cross section along the axis of symmetry was defined mathematically. The shape with the defining equations is shown in Figure 3.4. The radius of curvature increases from bow to stern, thus reducing the chance of flow separation. Reid (1987) has pointed out that the later Skyship designs bear some similarity to this shape, although the point at the stern is rounded off as inflated structures tend to droop if pointed.

The bare hull only represents part of the airship drag even when flying with no lift or yaw. The effect of other components on total drag is now considered.

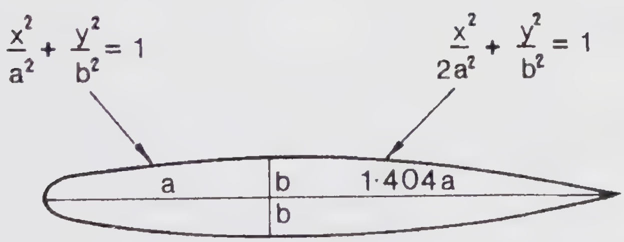


Figure 3.4. The NPL low drag airship body shape.

Effect of Additions to the Bare Hull

To make an operational airship it is necessary to provide control surfaces, propulsion unit(s) and accommodation for the crew and payload. Each of these items has a drag when measured on its own. This drag will be modified when it is fitted to the hull as it is then operating in the flow field of the hull. Conversely, each component will affect the flow around the hull so modifying its aerodynamic forces. Wind tunnel tests and fluid dynamic calculations have to be made for each design.

Durand (1934) contains component drag data for three airships which are reproduced as Table 3.3. The drag of each group of components is expressed as the flat plate area with the same drag. It also shows each component group's drag as a percentage of the total drag. The bare hull contributes about 50% of the total drag. While low hull drag remains an important objective, the minimisation of the drag of the whole design is the final goal.

The data in Table 3.3 were carefully estimated in a variety of ways but it is worth repeating Havill's observation verbatim. *"By attributing different degrees of importance to the various component data derived from indirect evidence, conclusions can be shifted somewhat."*

Table 3.3. *Drag Breakdown for three airships*

Estimated Drag Area Breakdown	**Bodensee**		**U.S.S. Los Angeles**		**U.S.S. Macon**	
Without Water Recovery	m^2	%	m^2	%	m^2	%
Bare hull	9.4	47.0	21.8	53.2	39.0	57.1
Fins and rudders	2.5	12.5	4.9	12.0	14.0	20.5
Wing power cars or outrigger gears, their suspension, ladders, struts, hoods, radiators, exhaust mufflers.	2.8	14.0	6.8	16.6	10.7	15.7
Rear power car with handling rails and bumpers.	2.4	12.0	2.2	5.3		
Control car or passenger car with handling rails and bumpers.	2.4	12.0	4.5	11.0	2.8	4.1
Miscellaneous protrusions - Mooring mast equipment, hoods etc.	0.5	2.5	0.8	1.9	1.8	2.6
Total	20.0	100	41.0	100	68.3	100
$(\text{Volume})^{2/3}$	790		1845		3528	
Resistance Coefficient C	0.025		0.022		0.019	

To illustrate the modification to the hull pressure caused by the gondola, Figure 3.5, produced from data contained in Gomes (1989c), shows the pressure distribution along the top and bottom of a wind tunnel model of the Sentinel 5000 hull with and without gondola. Curves C & D are for the clean hull; at zero incidence they are virtually identical. Curve B is for the top of the hull fitted with the gondola and, as expected, there is little change from curves C & D. However, curve A for the lower surface where the gondola is fitted shows considerable change. As might be expected the pressure rises ahead of the gondola. Unfortunately the two static tappings nearest to the gondola were blocked so the shape of the pressure curve over it is not known. Aft of the gondola the flow accelerates back to a slightly higher speed than the without gondola case. The increase of static pressure over the gondola will contribute to the aerodynamic lift of the airship. There is no evidence from this case that the gondola has affected the flow at the rear of the hull.

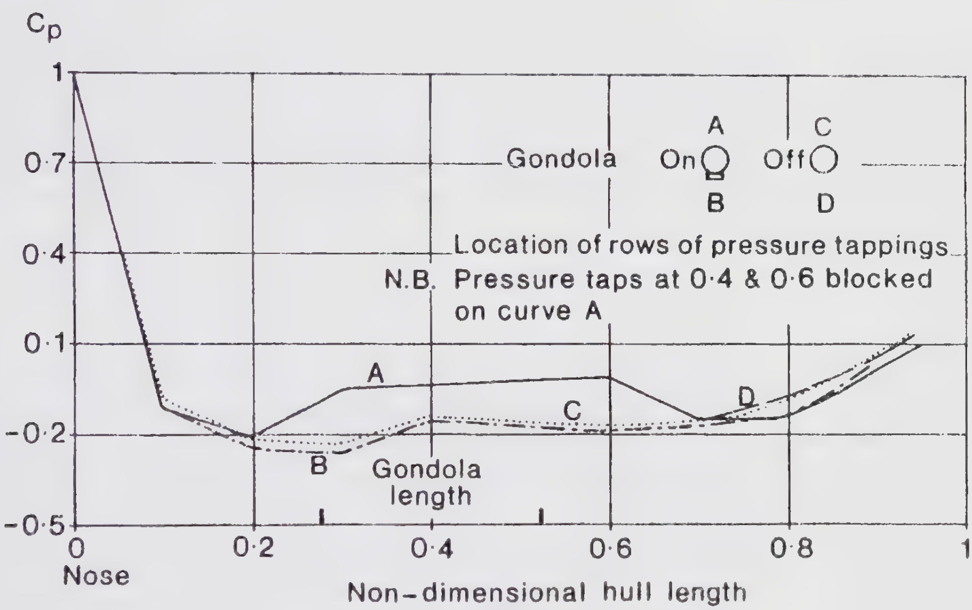


Figure 3.5. Effect of gondola on pressure distribution of Sentinel 5000 airship.

Curtiss, Hazen and Putman (1976) have compiled information on tail drag compared with bare hull drag; this is copied as Table 3.4. The bottom line of the Table shows the considerable variation in the results. This may be due to the accuracy of the methods used to obtain the data, but it also must reflect the differing aerodynamic interference which occurs. As a first approximation the regression line to the data in the bottom line of Table 3.4 is:

$$\frac{\text{Tail Drag per unit area}}{\text{Hull Drag per unit area}} = 3.56 - 0.195(l/d) \tag{3.8}$$

Table 3.4. *Tail drag compared to bare hull drag*

Airship	Bod.	R29	R32	R33	R38	L.A.	Akr.
Thickness Ratio	0.149	0.098	0.122	0.122	0.122	0.145	0.167
Wetted area of Tail / Wetted area of Hull	~0.1	0.08	0.06	0.06	0.07	0.07	0.11
Drag of Tail / Drag of Hull	0.27	0.18	0.07	0.12	0.07	0.22	0.24
Tail drag/Unit area / Hull drag/Unit area	~2.7	2.2	1.2	2.0	1.0	3.1	2.2

Bod. = Bodensee, L.A. = Los Angeles, Akr. = Akron

Attaching two bodies together in an airflow results in the flow about each being modified. A fin on an airship results in the local velocity over the hull, outside the boundary layer, being increased due to the flow blockage of the fin. This leads to an increase of skin friction drag and may also affect the local pressure distribution. Figures 3.6 & 3.7, also from Gomes (1989c), show the pressures on the hull in the vicinity of a fin.

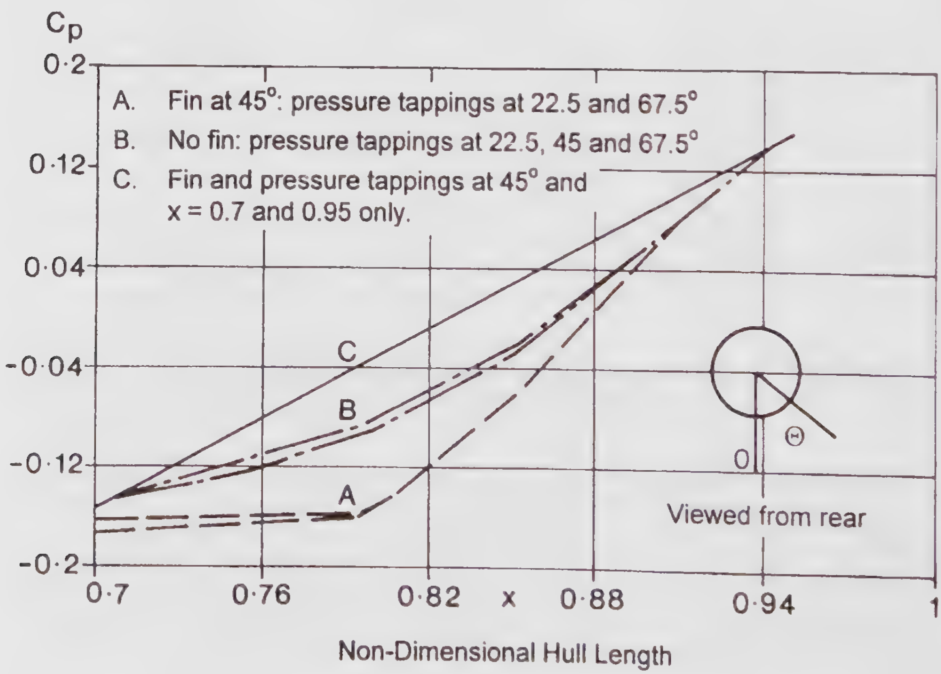


Figure 3.6. Effect of undeflected ruddervator on hull pressure distribution.

The fin is aligned along the line through the 45° point on the central meridian. The three curves in Figure 3.6 labelled B relate to the bare hull. As expected for an axisymmetric body at zero incidence they are virtually identical. Adding the fin blocked the static tappings between x = 0.8 and 0.9 so curve A only shows that the pressure up and downstream of the fin is similar to that of the static rows shown in curve C. The reduction in static pressure, indicating a higher velocity, due to the fin is apparent by comparing curves A & B. This velocity change will increase the form drag as the slope of the hull gives the force a rearward component. The change of velocity gradient may also affect the drag by altering the boundary layer separation.

Figure 3.7 shows the further change in surface pressures when the control surface is deflected. The increase in static pressure for curves o & a and the reduction for curves c & d in the right hand relative to the left hand diagram is due to the lift induced circulation around the ruddervator. This term indicates that the control surfaces on the fins act as elevators when all are deflected in the same sense and as rudders when the deflections of diagonally opposite pairs are in the opposite sense.

Owing to the length of airship hulls, the boundary layer is thick at the stern. Hoerner (1957) provides formulae for the thickness of the boundary layer s (i.e. distance from the surface at which the velocity is 99% of local inviscid free stream value) on a body of revolution aligned with the wind. If the maximum body diameter d occurs a distance x_m behind the nose, then:

$$\begin{aligned} s &= 0.02x && \text{for } x < x_m \\ s &= 0.02x(d/d_x) && \text{for } x > x_m \qquad (3.9) \end{aligned}$$

where: d_x is the diameter of the body distance x behind the nose. The constant of 0.02 was derived for aircraft fuselage surface finish quality: changes from that standard will alter this value. Within the boundary layer the reduced velocity reduces the drag of the fin. For the YEZ-2A this formula gives a value of s in the mid-fin position of about 3m which is nearly half the height of the fin. However, the displacement thickness (i.e. the thickness of a layer of stagnant fluid on the surface that has the same integrated velocity defect as the actual boundary layer) is about 1/4 of s or in the case of the YEZ-2A about 12% of the height of the fin.

Estimating control car drag may be done using information in Hoerner (1957) which is based on experimental tests of cockpit shapes. His results suggest a drag coefficient of 0.09 based on the frontal area of the car. He does qualify this with the statement, "*Taking into account, however, the gaps, edges and other surface irregularities of the canopy as actually constructed, its drag is probably twice as high as found on smooth wind-tunnel models.*" The value of the velocity used to convert drag coefficient to drag force is the local velocity around the hull.

No published breakdown of drag exists for a modern airship. However, the total airship drag coefficient of a Skyship 500 was experimentally determined from flight tests as 0.032 by Bailey (1985). This value is significantly higher than those given in Table 3.2 but the Skyship is smaller and therefore operates at a lower Reynolds number.

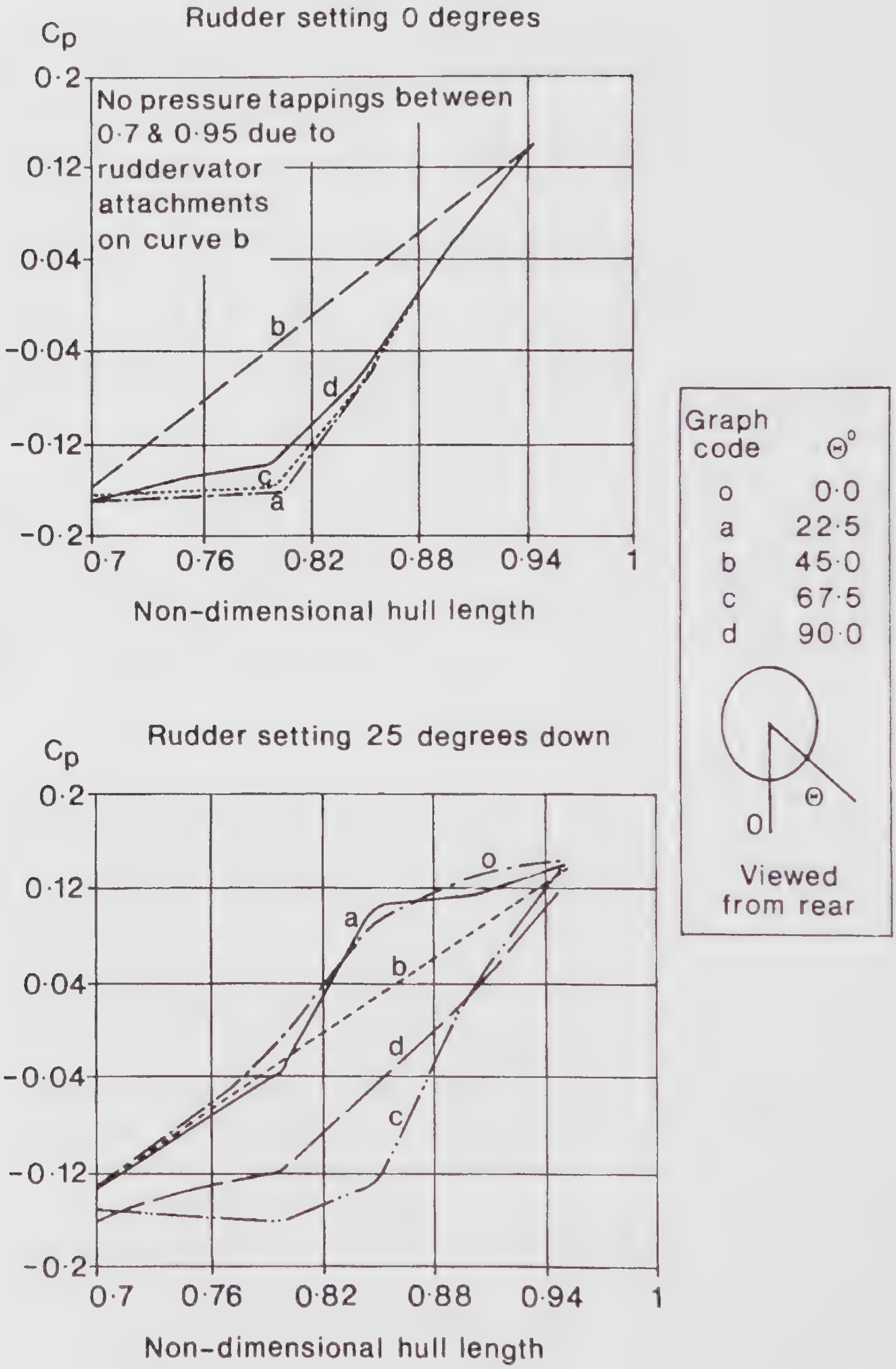


Figure 3.7. Effect of ruddervator deflection on hull pressure distribution.

The bare hull drag coefficient calculated using Equation 3.7 is $C_{DV} = 0.017$, i.e. just under half of Bailey's measured figure. This is in good agreement with the examples quoted in Table 3.2. The drag of the tail calculated using Equation 3.8 increases the hull figure by 29%. The drag of the control cabin using a $C_D = 0.18$ increases C_{DV} by 0.0064, which gives a total $C_{DV} = 0.0283$. There are further contributions to be added including propulsion units, landing gear and mooring attachments. The agreement with Bailey's figure is acceptable.

DYNAMIC FORCES

A body in motion, even in an ideal fluid, displaces that fluid. Each fluid particle is displaced in the direction of the motion of the body. The magnitude of that movement is related to the distance from the path of the body. The fluid therefore gains kinetic energy which can be calculated using potential flow theory. The reader who is unfamiliar with this theory is referred to standard texts such as Milne-Thomson (1955).

Apparent Mass Determination

If w is the complex potential of a flow then the kinetic energy in the fluid T_f is given by:

$$T_f = -0.25\, i\rho \int w\, d\bar{w} \qquad (3.10)$$

where: i is $\sqrt{-1}$ and $\bar{w}$ is the complex conjugate of w.

For the case of a circular cylinder of radius a:

$$w = Ua^2/z, \quad \bar{w} = Ua^2/\bar{z}, \quad d\bar{w} = Ua^2\, d\bar{z}/\bar{z}^2.$$

On the cylinder $z = a\,e^{i\theta}$. Substituting these expressions into Equation 3.10 gives:

$$T_f = 0.5\, \pi \rho a^2 U^2 \qquad (3.11)$$

The mass of fluid per unit thickness displaced by the cylinder is $M' = \pi \rho a^2$. If M is the mass of the cylinder per unit thickness the total kinetic energy of fluid and cylinder T is:

$$T = 0.5(M + M')U^2 \qquad (3.12)$$

Let F be the resultant external force on the cylinder, so:

$$FU = dT/dt = (M + M')U\, dU/dt \qquad (3.13)$$

since the rate of change of kinetic energy equals the work done by the external forces. Rearranging gives:

$$F - M'dU/dt = MdU/dt \tag{3.14}$$

In the absence of the fluid the second term would be absent and the normal dynamic equation of motion results. The cylinder experiences a resistance to its motion due to the fluid of M'dU/dt per unit thickness. M' is called the added mass. It will be observed that if U is constant then there is no added mass. The physics behind this process was best explained by Darwin who is quoted in Milne-Thomson (1955). The following is based on the relevant section of that book.

Consider the steady motion of a circular cylinder of radius 'a' moving through a perfect fluid of density ρ with velocity U. Figure 3.8 shows the motion of three fluid particles relative to a fixed observer as the cylinder moves from $-\infty$ to $+\infty$.

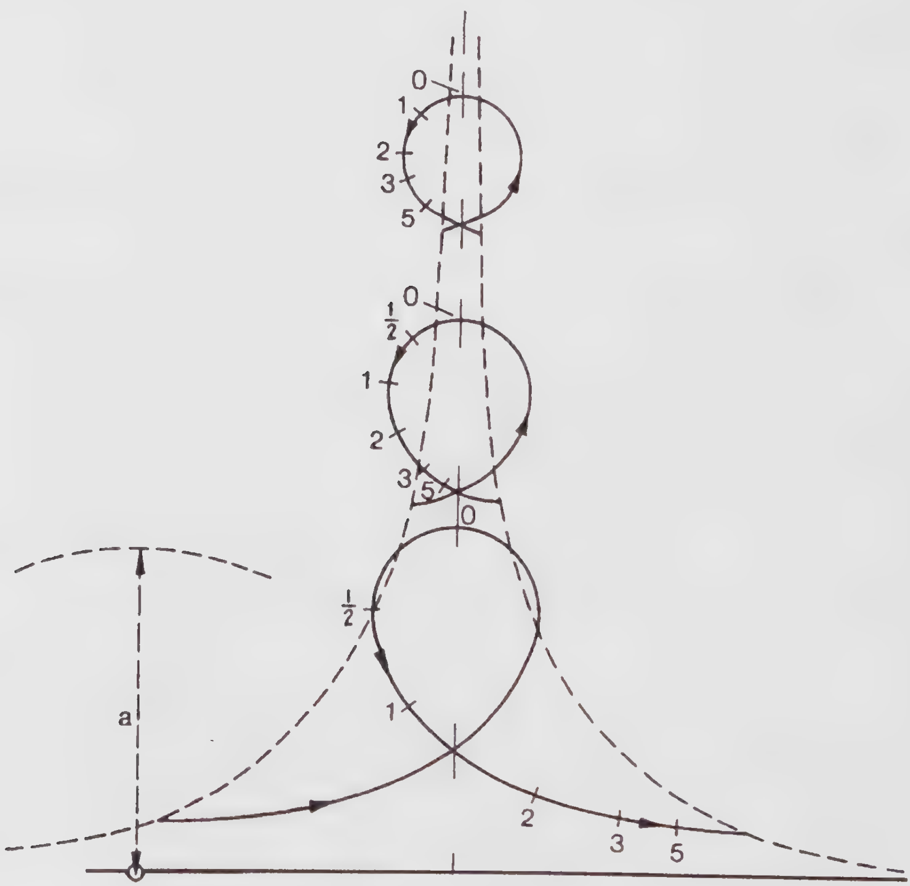


Figure 3.8. Fluid particle paths during passage of circular cylinder.

The equation of the streamlines is:

$$1/R \;=\; 4\,(y - \nu/2)/a^2 \tag{3.15}$$

where: R is the radius of curvature and ν the streamline variable. When the cylinder is at -∞ all the particles lie on the broken curved line on the left of the Figure. When the cylinder reaches +∞ they lie on the right hand broken line. The numbers on the curves show the particles' position when the cylinder has advanced that number of radii from the central position. It is obvious that a mass of fluid has drifted towards the right of the diagram during the cylinder's transit. This 'drift' for any particle is evaluated by considering motion relative to the cylinder regarded as fixed. The drift ξ is then:

$$\xi \;=\; \int_{-\infty}^{+\infty}(U+dx/dt)dt \tag{3.16}$$

This integral can be evaluated in terms of elliptic functions. For unit thickness the mass of the fluid which has drifted is:

$$\rho\int_{-\infty}^{+\infty}\xi.d\nu$$

where: ν is the streamline variable. On evaluation the drift mass equals the mass of fluid displaced by the cylinder which is the same result found in Equation 3.11 above.

The importance of using the apparent mass (M + M') in place of physical mass M depends on the relative densities of the cylinder and the fluid. For buoyant craft these densities are very similar and apparent mass is important.

The use of the complex potential to obtain the added mass of a body has been used for two- and three-dimensional shapes. Milne-Thomson (1955) gives results for the following bodies.

For an elliptic cylinder with minor axis 2b and major axis 2a which is inclined to the flow at angle α, $\mathbf{M' = \rho\pi(b^2\cos^2\alpha+a^2\sin^2\alpha)}$. It will be noted that this corresponds to the area of a circle with a diameter equal to the projected width of the ellipse normal to the incident flow.

For an ellipsoid with equation $x^2/a^2 + y^2/b^2 + z^2/c^2 \;=\; 1$,

$$M' \;=\; 1.33\rho\pi abc\;\alpha_0/(2 - \alpha_0) \tag{3.17}$$

where:

$$\alpha_0 = \int_0^{+\infty} abc\; d\lambda \;/\; \left\{\left(a^2+\lambda\right)^{1.5}\left(b^2+\lambda\right)^{0.5}\left(c^2+\lambda\right)^{0.5}\right\}$$

The general solution is evaluated using elliptic integrals. However, for an ellipsoid of revolution when b = c, which is relevant for airships, then:

$$\alpha_0 = 2\{(1-f^2)/f^3\}\{0.5\ \mathrm{Ln}[(1+f)/(1-f)] - f\}$$

where: $f = (1 - b^2/a^2)^{0.5}$. In the limiting case of the sphere, when $b = a$, $\alpha_0 = 2/3$ so the added mass is half of the mass of the fluid displaced. If the ellipsoid is moving parallel to either the y or z directions then expressions similar to α_0 exist. An expression may also be found if the ellipsoid is rotated about its z axis, i.e. it is yawing.

Munk (1924) applied this information to determine forces and moments on airships. {Readers may find it easier to locate his work in his contributions to Durand (1934)}. His method was to modify the body mass with an inertia coefficient to account for the added mass. He examined both two- and three-dimensional problems.

For two-dimensional cases, such as sections of the hull in a cross flow, the shape is approximately elliptic. Munk proposed that η be defined as:

$$\eta = \pi c^2/4\,S \tag{3.18}$$

where: c is the largest width at right angles to the motion considered and S the area of the cross section. If the section is circular $\eta = 1$. He points out that even in the case of pear shaped bodies the error in this approximation is small. The area of apparent mass is ηS.

The apparent mass of the hull is affected by its geometry with the shape of the bow and stern having most significance for axial motion. This is not surprising as the disturbance of the surrounding fluid reduces as the shape becomes more streamlined. Hence the drift mass reduces. Munk suggested two methods of force estimation for three-dimensional bodies.

The first approach resolves the incident flow along the body principal axes. For lateral motion the body is then divided into slices parallel to the incident flow component. The inertia factor for each slice is then calculated using Equation 3.18. The overall factor is then obtained by integration.

The second method fits the hull shape with an ellipsoid of revolution with the same meridian cross section area S' and length L as the hull. The thickness ratio is then:

$$b/a = 4S'/\pi L^2$$

Inertia factors, k_1 ,k_2, k' of this ellipsoid in axial, lateral and rotational motion about the z-axis, yawing motion, may be calculated generally. For axial motion the relevant formulae are given at Equation 3.17. The equivalent expressions for the lateral and rotational cases may be deduced similarly or found in Milne-Thomson (1955) sections 16.52 and 16.53, page 485. The values for the inertia factors for ellipsoids of revolution are given in Table 3.5. If the hull is not circular in cross section then the appropriate inertia factors are ηk_1, ηk_2 and $\eta k'$ where η is given for a cross section by Equation 3.18 or by its average value over the length.

Table 3.5. *Inertia coefficients of an ellipsoid of revolution*

Thickness Ratio	Direction of Motion		
	Axial	Transverse	Rotation
0.1	0.017	0.96	0.89
0.111	0.02	0.955	0.87
0.125	0.025	0.95	0.83
0.143	0.03	0.94	0.81
0.167	0.05	0.92	0.77
0.2	0.07	0.89	0.70
0.25	0.09	0.86	0.61
0.333	0.12	0.80	0.47
0.5	0.21	0.70	0.23
1.0	0.50	0.50	0.00

The Determination of Body Forces and Moments

If a body is moving steadily through a fluid, its motion may be defined by translation $\underline{U}$ and rotation $\underline{\omega}$ vectors related to axes fixed in the body. If $\underline{\xi}$ is the momentum and $\underline{\lambda}$ the moment of momentum vectors, then the normal equations of motion are:

$$\delta\underline{\xi}/\delta t = \underline{\omega} X \underline{\xi} + \underline{X} \quad \delta\underline{\lambda}/\delta t = \underline{\omega} X \underline{\lambda} - \underline{U} X \underline{\xi} + \underline{L} \tag{3.19}$$

where: $\underline{X}$ and $\underline{L}$ denote an external force and moment respectively.

Flight at Incidence

Consider a body of rotation flying steadily at incidence α. If unit orthogonal vectors $\underline{i}$, aligned along the axis of symmetry of the body with $\underline{j}$ and $\underline{\kappa}$ to the side and upward respectively then:

$$\underline{U} = u\underline{i} + \underline{w\kappa} = U(\underline{i}\cos\alpha + \underline{\kappa}\sin\alpha)$$

If the apparent mass in the two vector directions is A and B then:

$$\underline{\xi} = AU\underline{i}\cos\alpha + BU\underline{\kappa}\sin\alpha$$

Substituting into Equation 3.19, noting that the left hand sides are zero as the motion is steady and that $\underline{\omega} = 0$, then:

$$\underline{X} = 0 \quad \underline{L} = \underline{U} \, X \, \underline{\xi} = (B - A)U^2\cos\alpha\sin\alpha \, \underline{j} \tag{3.20}$$

No force is generated on the hull but there is a nose up pitching moment, if α is positive, which will rotate the hull until the axis of symmetry is vertical. But A = $\rho(\mathrm{Vol})k_1$ and B = $\rho(\mathrm{Vol})k_2$ so the magnitude of the nose up pitching moment M is:

$$M = \tfrac{1}{2}\rho\, U^2(\mathrm{Vol})(k_2 - k_1)\sin 2\alpha \tag{3.21}$$

where: (Vol) is the hull volume. This pitching moment has to be countered in steady flight and this is done by the tail surfaces. These produce a lift force equal to M/l_1 where l_1 is the distance from the centre of lift of the fins to the centre of the hull. The airship, therefore, always has some dynamic lift if the hull is flown at an incidence, although the inviscid flow model shows - as expected - that no lift is generated on the hull.

Steady Turning Flight

An airship flying a steady circular course of radius r is shown in Figure 3.9. The centre of gravity of the hull moves with velocity V along the tangent to the flight path; the hull centre line flies with an angle of yaw, ϕ. To maintain this attitude the hull has an angular yaw velocity of $V\cos\phi/r$. Thus the velocity components U_x and U_y of cross section area S at position x are:

$$U_x = V\cos\phi, \quad \text{and} \quad U_y = V\sin\phi + xV\cos\phi/r$$

The rate of change of momentum per unit length of the body is:

$$d/dt(\rho S.U_y) = U_x.d/dx(\rho S.U_y) = \rho V^2\sin 2\phi dS/dx + (S + xdS/dx)\rho V^2/r \tag{3.22}$$

The force distribution along the hull corresponding to each of these terms is shown in Figure 3.9. Curve b is the distribution that gives rise to the moment discussed in the section, *Flight at Incidence* The moment here tends to tighten the radius of the turn and rudder(s) deflection is needed to maintain the constant radius. In this case the 'incidence' is the yaw angle. The second term, curve c, represents the aerodynamic forces combating the centrifugal acceleration owing to the curved path flown while curve d is the equivalent of the first term but the 'incidence' is caused by the angular velocity of the body. It is worth noting that the incidence of the rudder(s) is increased by the angular velocity of the hull which enhances their effectiveness.

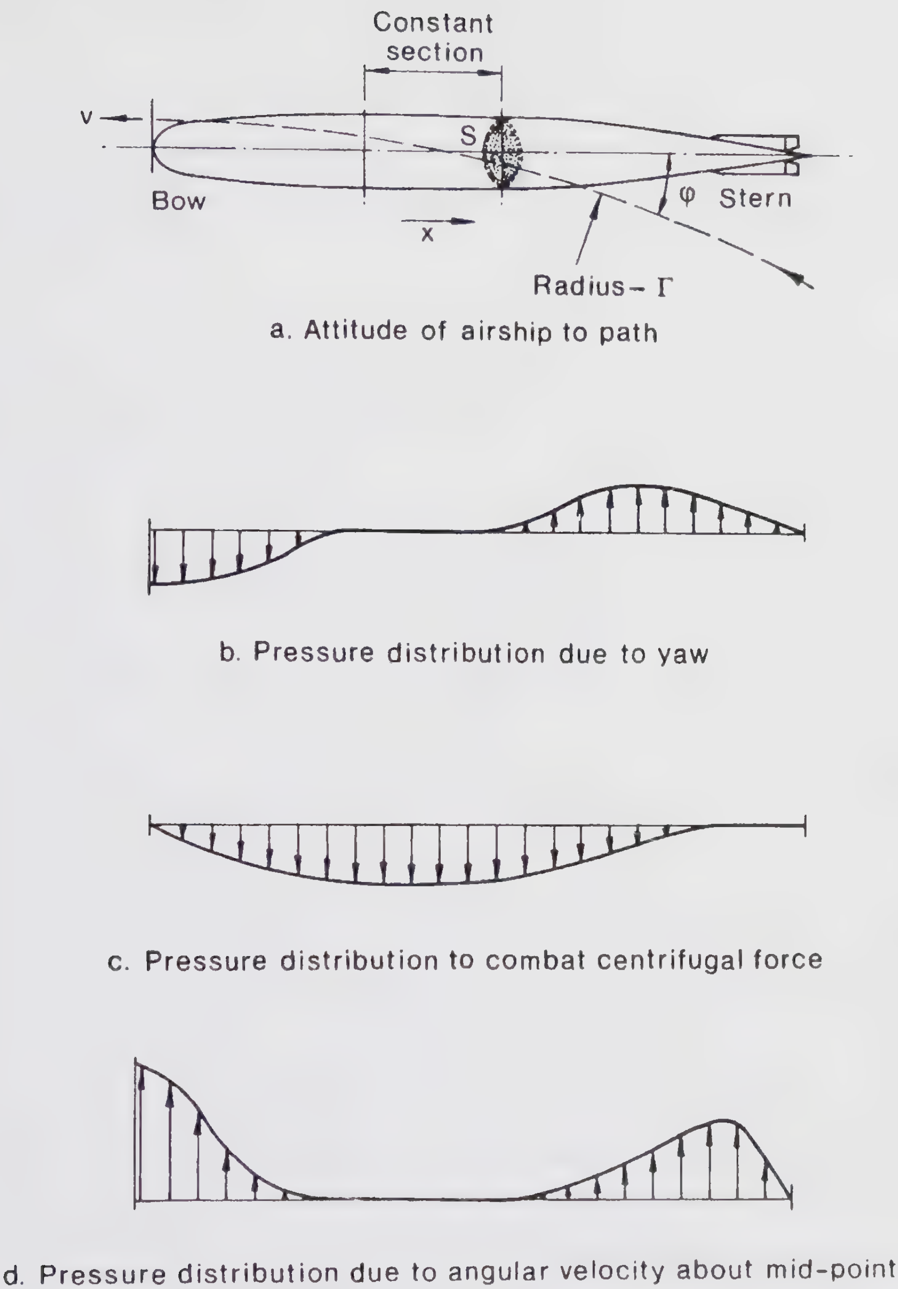


Figure 3.9. Forces developed on an airship in curved flight.

The inherent instability of the airship is never completely corrected by the fins. This is partly for reasons of fin weight and size, the latter for ground handling and hanger size, and because an airship turn may be induced more easily as the instability swings the nose into the turn. The penalty is that the helmsman, or flight control system, has to correct any disturbance induced change of heading. It has been found that the aerodynamic forces increase more rapidly than linearly with ϕ. Thus with rudder zero the airship settles into a small but steady rate of turn in the direction induced by a disturbance. There is therefore a hysteresis effect in the response to rudder movement about zero deflection which is shown in Figure 3.10 taken from Arnstein and Klemperer (1934).

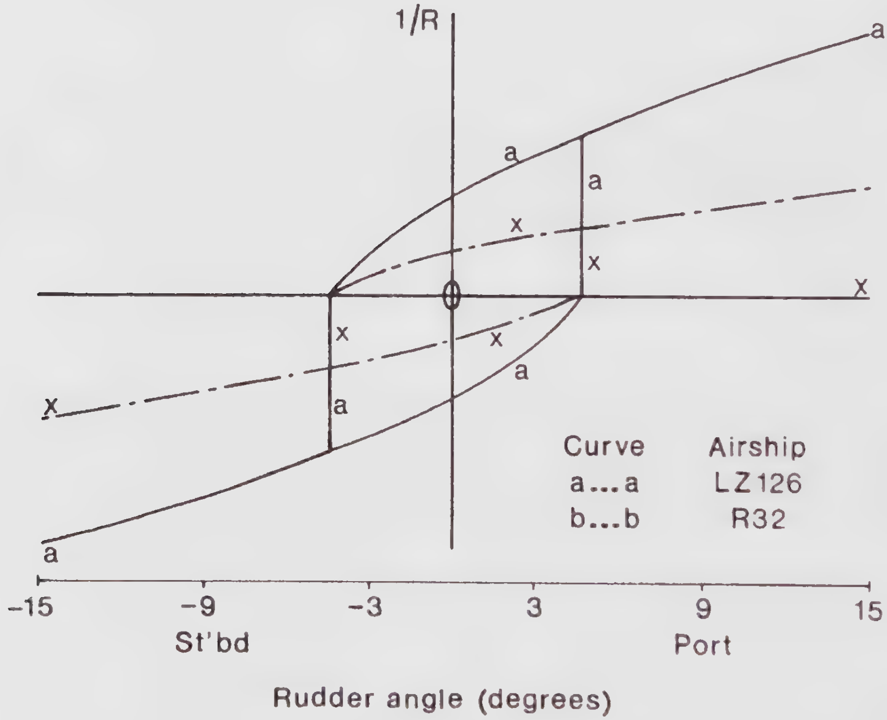


Figure 3.10. Airship path curvature vs. rudder angle.

SLENDER BODY THEORY

In calculating forces on a body of revolution, like an airship hull, Munk made the assumption that it was slender. A body is slender if the length is large compared with the maximum diameter and the rate of change of diameter along the length is small. The last condition allows the axial component of velocity at all sections to be assumed to be identical to the component of the free stream. The cross flow is then two-dimensional in the plane normal to the long axis. For a circular cross section the pressure distribution can be calculated easily in inviscid flow.

For any circular section the velocity potential Φ is:

$$\Phi \quad = \quad -U_y(r + R^2/r)\cos\theta$$

where: U_y is the cross flow velocity, R the radius of the cross section and r,θ the polar co-ordinates with the pole at the centre of the circle. If β is the slope of the surface in the axial, x, direction, i.e. $\tan\beta = dR/dx$, then the pressure p at any point on the circular section is:

$$(p\text{-}p_0)/\rho \quad = \quad \int_0^{2\pi} \; 2U_xU_y(R/r)\tan b \cos q \sin 2a\text{-}0.5U_y^2(1\text{-}4\sin^2 q)\sin^2\alpha \qquad (3.23)$$

If $P \;=\; (p - p_0)/\rho$, then Equation 3.24 may then be written as:

$$P \quad = \quad P_{\alpha=0} + 2\tan\beta \sin 2\alpha \cos\theta \; + (1\text{-}4\sin^2\theta)\sin^2\alpha \qquad (3.24)$$

where: $P_{\alpha=0}$ is the pressure distribution on the circular section at $\alpha = 0$. Owing to body incidence the force, f, on the cross section per unit length is given by:

$$f \;=\; (P\text{-}P_{\alpha=0})R\cos\theta\, d\theta \;=\; q_0 2\pi R(dR/dx)\sin 2\alpha \;=\; q_0 dS/dx \sin 2\alpha \qquad (3.25)$$

where: S is the area of cross section of radius R.

Ward (1949) showed that this force is directed midway between the normal to the axis of revolution and the normal to the wind direction, i.e. $\alpha/2$. Equation 3.25 is therefore multiplied by $\cos\alpha/2$.

Allen and Perkins (1951) extended this analysis to make allowance for viscous effects. Using Equation 3.24 they computed the pressure distribution around several sections along the hull which were then compared with experimental data measured by Freeman (1932) on a 1/40th scale wind tunnel model of US airship 'Akron'. Figure 3.11 is copied from their work. Flow separation occurs in an adverse pressure gradient and that is clearly shown in this Figure. Over the forward sections of the hull, x/L = 0.111, where the pressure gradient is negative, calculated and measured results agree well. Aft of the centre of the body an adverse gradient exists and flow separation may occur, any separation becoming more severe the nearer the section is to the tail as shown at x/L = 0.867. Allen and Perkins realised that if the body pressure distributions were viewed sequentially from nose to tail, there was a strong similarity to the time history of a circular cylinder's pressure distribution as the flow is accelerated from rest. In that flow regime vortices were shed behind the cylinder; photographs of such a flow are shown on plate 1 of Milne-Thomson (1955).). Viewed three-dimensionally the vortex elements from each body section combine to form line vortices along the length of the body. Allen and Perkins found flow visualisation photographs taken on missile and other slender bodies showed these trailing vortices. Since details of this flow and the drag coefficient are Reynolds number dependent they suggested an additional term be added to Equation 3.25 to approximate for these viscous effects. This term is the drag of a circular cylinder at the Reynolds number Re for a stream velocity of Usin α and a diameter of 2R at lengthwise location x. Equation 3.25 becomes:

$$f = q_0 dS/dx \sin 2\alpha \cos \alpha/2 + 2R\, C_{D\,(Re)}\, q_0 \sin^2 \alpha \qquad (3.26)$$

where: $C_{D(Re)}$ is the appropriate drag coefficient.

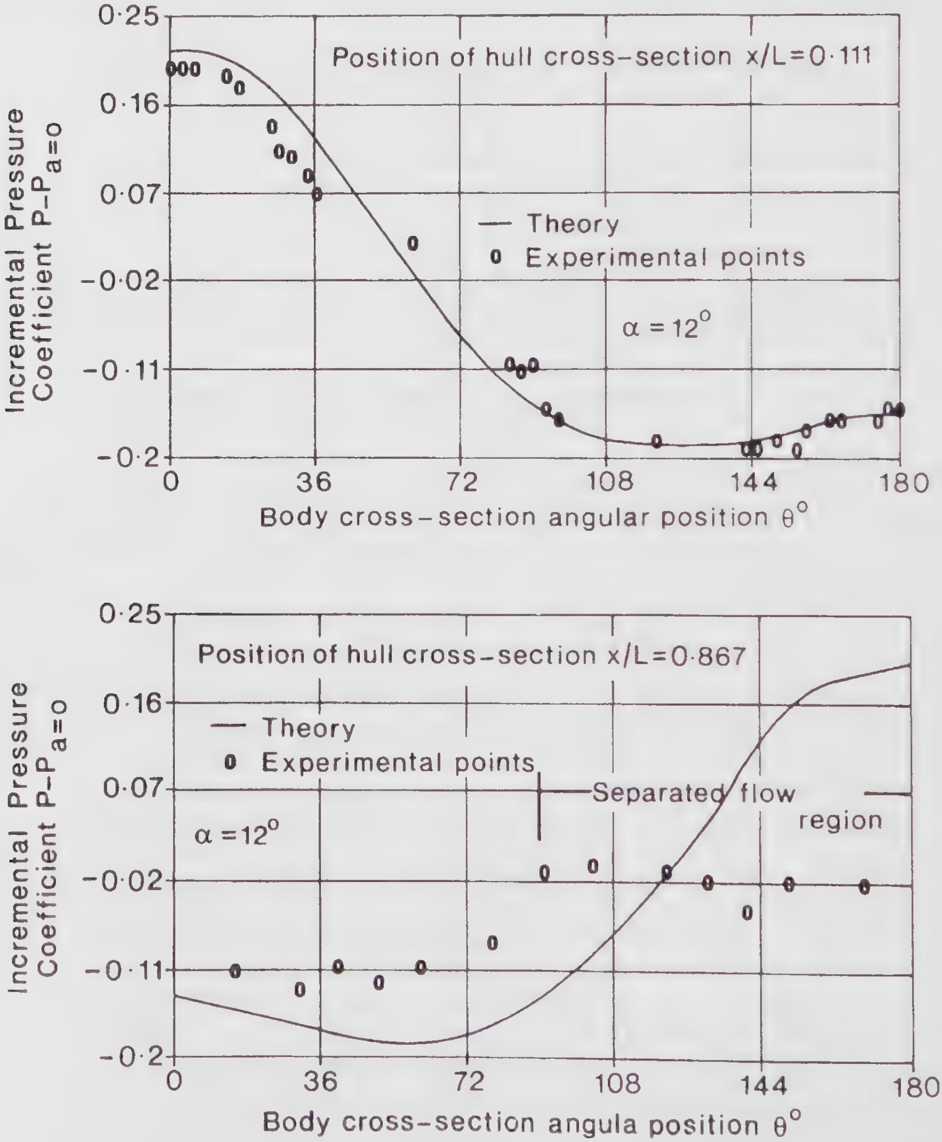


Figure 3.11. Comparison of theory and experimental incremental pressure coefficients for U.S.S. Akron.

AN ESTIMATION METHOD FOR OVERALL AERODYNAMIC FORCES AND MOMENTS

Equation 3.26 has been used by Jones and DeLaurier (1981) to provide a method for estimating airship forces and moments. They followed Munk in noting that airship hulls have conicity, which means that the surface pressures on a cross-flow section result in both lateral and axial forces. Equation 3.21 allowed for this effect with the factor $(k_2 - k_1)$ so the first term in Equation 3.26 becomes:

$$q_0 dS/dx(k_2 - k_1)\sin 2\alpha \cos \alpha/2.$$

Their schematic of the airship steady state analytical model is shown in Figure 3.12. The hull is considered from the nose to the start of the fins, l_h. Aft of that station it is included with the fin aerodynamics. Hull forces are evaluated on a typical section situated between l_i and l_{i+1} using Allen and Perkins and then summed. Fin forces are estimated using one of a number of well established finite wing methods. Jones and DeLaurier (1981) use Wardlaw (1979) for values of $(C_{Dc})_h$ and $(C_{Dc})_f$. $(C_t)_f$ is a correction to Wardlaw as the fins do not have sharp leading edges. These results are multiplied by efficiency factors, η_k to allow for the effect of the fins on the hull and η_f the effect of the hull on the fins. These factors have been obtained empirically by a least squares fit to experimental data.

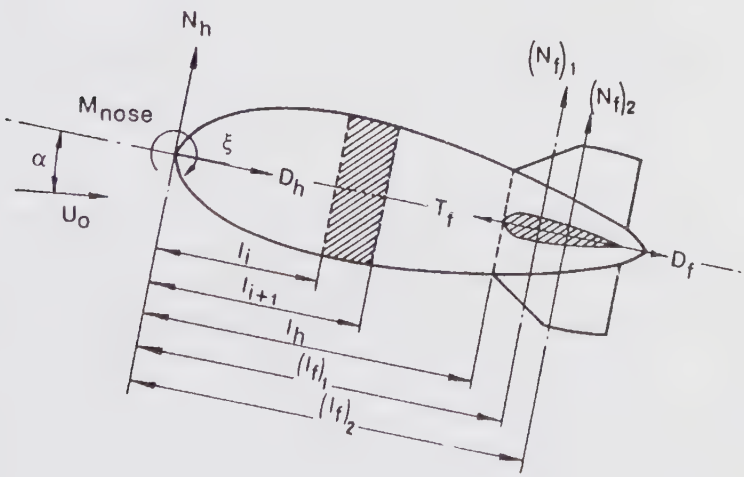


Figure 3.12. Schematic of steady-state analytical model.

The normal, C_n, and axial, C_D, force and pitching moment, $(C_m)_{nose}$, coefficient equations are:

$$C_n = [(k_2-k_1)\,\eta_k\, I_1+0.5(C_{n\alpha}^*)_f\,\eta_f\, S_f]\sin 2\alpha + [(C_{Dc})_h\, J_1+(C_{Dc})_f\; S_f]\sin\alpha\,\sin|\alpha| \tag{3.27}$$

$$C_D = [(C_{Dh})_0 S_h + (C_{Df})_0\, S_f]\cos^2\alpha - (k_2-k_1)\eta_k\, I_1 \sin 2\alpha\,\sin(\alpha/2)-(C_t)_f S \tag{3.28}$$

$$(C_m)_{nose} = -\,[(k_2-k_1)\,\eta_k\, I_3+0.5\,(l_f)_1\,(C_{n\alpha}^*)_f\,\eta_f\, S_f]\sin 2\alpha - (C_{Dc})_h\, J_2 + (C_{Dc})_f\,(l_f)_2\, S_f]\sin\alpha\,\sin|\alpha| \tag{3.29}$$

where:

- C_n C_D are made non-dimensional with $q_0(\mathrm{Vol})^{2/3}$
- $(C_m)_{nose}$ with $q_0(\mathrm{Vol})^{2/3}L$, where L is the total hull length
- S_f = fin(s) reference area S_f (fig 13)/$(\mathrm{Vol})^{2/3}$
- S_h = hull reference area /$(\mathrm{Vol})^{2/3}$
- S = hull cross section area at station ξ
- $I_1 = \int_0^{l_n} dS/d\xi\; d\xi\,/L$ $\qquad I_3 = \int_0^{l_n} \xi\, dS/d\xi\; d\xi\,/(\mathrm{Vol})^{2/3}L$
- $J_1 = \int_0^{l_n} 2r d\xi/L$ $\qquad J_2 = \int_0^{l_n} 2r\xi\; d\xi/(\mathrm{Vol})^{2/3}L$
- $(l_f)_1$ and $(l_f)_2$ with L
- $(C_{Dc})_h$ = hull cross-flow drag coefficient /J_1L,
- $(C_{Dc})_f$ = fin(s) cross-flow drag coefficient /S_f
- $(C_{n\alpha}^*)_f$ = derivivative of isolated fin's normal force coefficient w.r.t. α @ α=0/S_f
- $(C_{Dh})_0$ = hull zero-angle axial drag coefficient /S_h
- $(C_{Df})_0$ = fin zero-angle axial drag coefficient /S_f
- $(C_t)_f$ = fin leading edge suction coefficient /S_f

The integrals depend only on the design geometry.

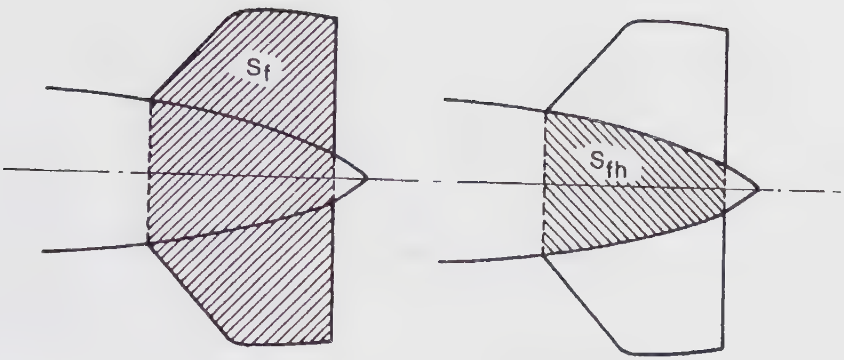


Figure 3.13. Definition of fin planform areas.

The fin geometry is shown in Figure 3.13. The carry-over of lift from fins across the dividing hull has been appreciated since 1910 when Prandtl and Fuhrmann showed that two fins separated by a body produced 60% more lift than the two fins directly joined together. Figures 3.6 and 3.7 discussed above show the effect. Data obtained on the model of the 'Akron' and separately on a model of the R101 suggest a slightly lower figure as illustrated in Figure 3.14, taken from Curtiss, Hazen and Putman (1976).

η_k and η_f are shown in Figure 3.15, taken from Jones and DeLaurier (1981). Γ is the dihedral angle of the fins. The interaction of the body vortices and those generated by the lift-producing fins can generate sharp local aerodynamic fin loadings. An example taken from the 'Akron' model tests of Freeman (1932) is shown in Figure 3.16.

Jones and DeLaurier's model brings a logic into the estimation of aerodynamic forces and moments. It is capable of further development but this is hampered by the absence of a large data base against which the method may be tested and refined. Readers intending to use the technique should refer to the original paper. The steady aerodynamic loading distribution on the body may be calculated using the equations before integration. Such information is essential for the structural designer.

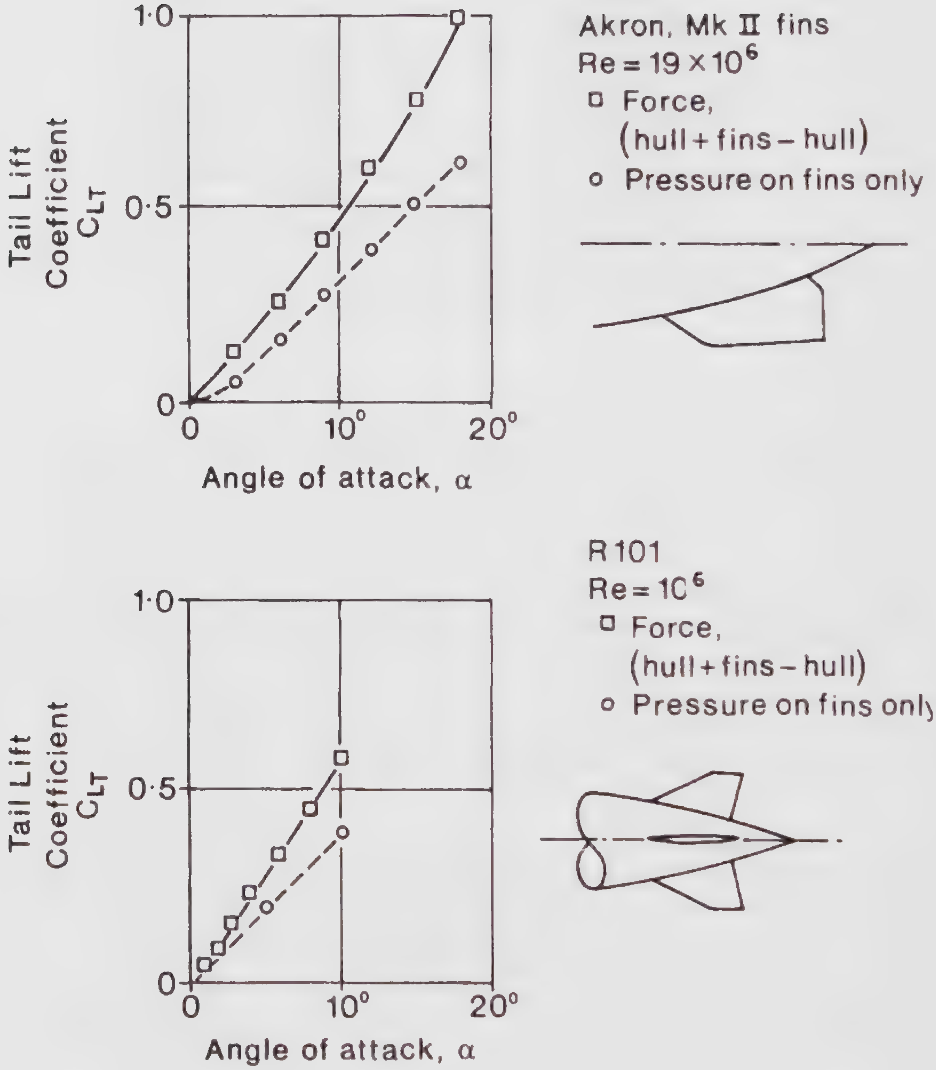


Figure 3.14. Influence of 'carry-over' lift on tail lift coefficient.

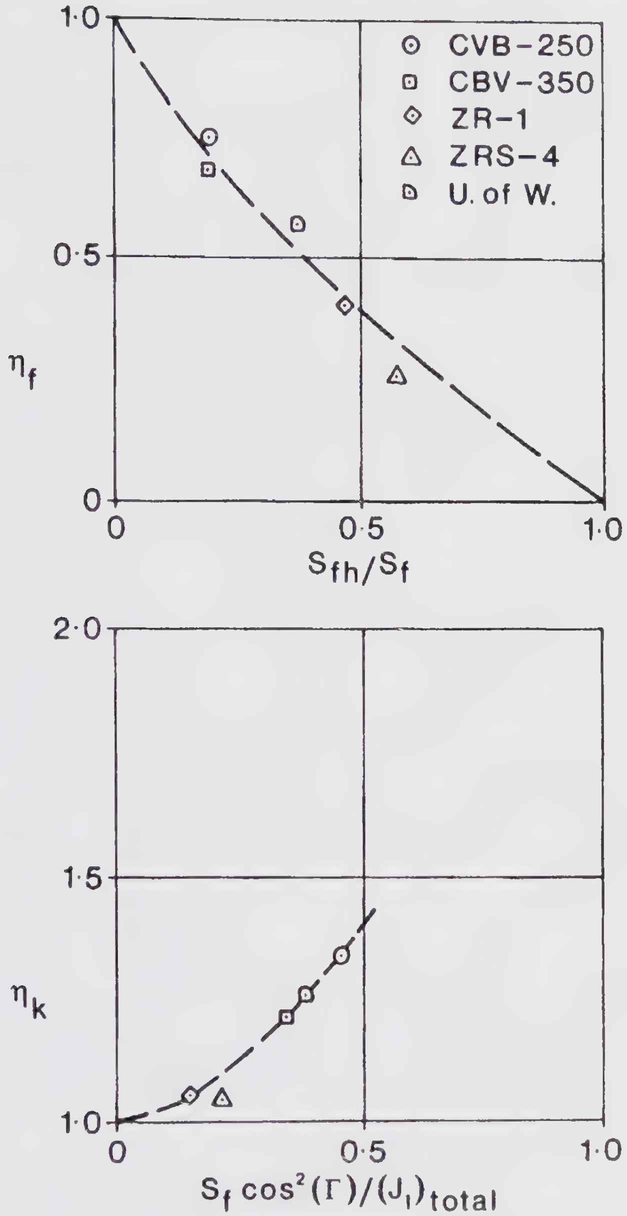


Figure 3.15. Fin and hull efficiency factors deduced from experimental data.

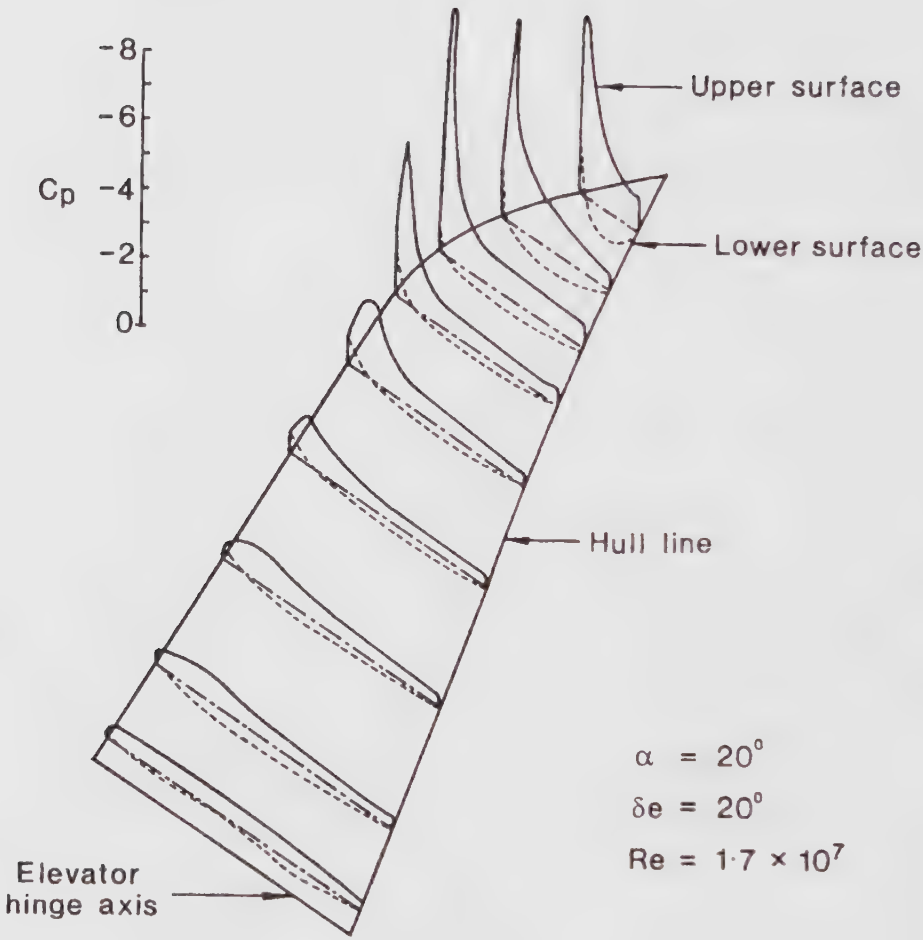


Figure 3.16. Fin distribution on 1/40th scale model of the Akron.

UNSTEADY AERODYNAMICS

The structural failure of airships, e.g. the Shenandoah, in conditions of severe atmospheric turbulence has led to the development of techniques to estimate structural loads in such conditions. These techniques are computational backed up with wind tunnel testing, the latter being discussed in the section on ***Wind Tunnel Testing***.

The computational method requires a model of the incident atmospheric turbulence and method of determining the vehicle's response.

A characteristic of turbulent flow is that the pressure measured at a point is random in nature. Representation of such a flow is therefore more difficult than for steady flows discussed previously. The representation of the time varying pressure (or velocity) at a point is expressed as a series of sine waves each with a characteristic amplitude Γ, frequency ω and direction in the appropriate frame of reference. Treating, for example, the vertical component of a gust w_g, the value at distance ξ from the origin fixed in the airship for gust component with frequency ω is:

$$w_g = U_0 \Gamma \exp\{i\omega t - i\omega \xi \cos(\alpha_0/U_0)\} \tag{3.30}$$

where: α_0 is the steady incidence and U_0 the airship velocity.

The response to each component of turbulence may be evaluated, for example by inserting w_0/U_0, which is the local incidence at ξ, into Equations 3.27-3.29 above. The resulting forces and moments are then evaluated on the assumption that a quasi-steady model is appropriate. Owen (1973) gives an example of such an approach and also explains the results. Using slender body theory he computed the response of a mathematically simple airship-like rigid body. Since slender body theory only uses the variation of cross section area S, he specified the variation along its length l ($0 \le x \le 1$) by the parabola:

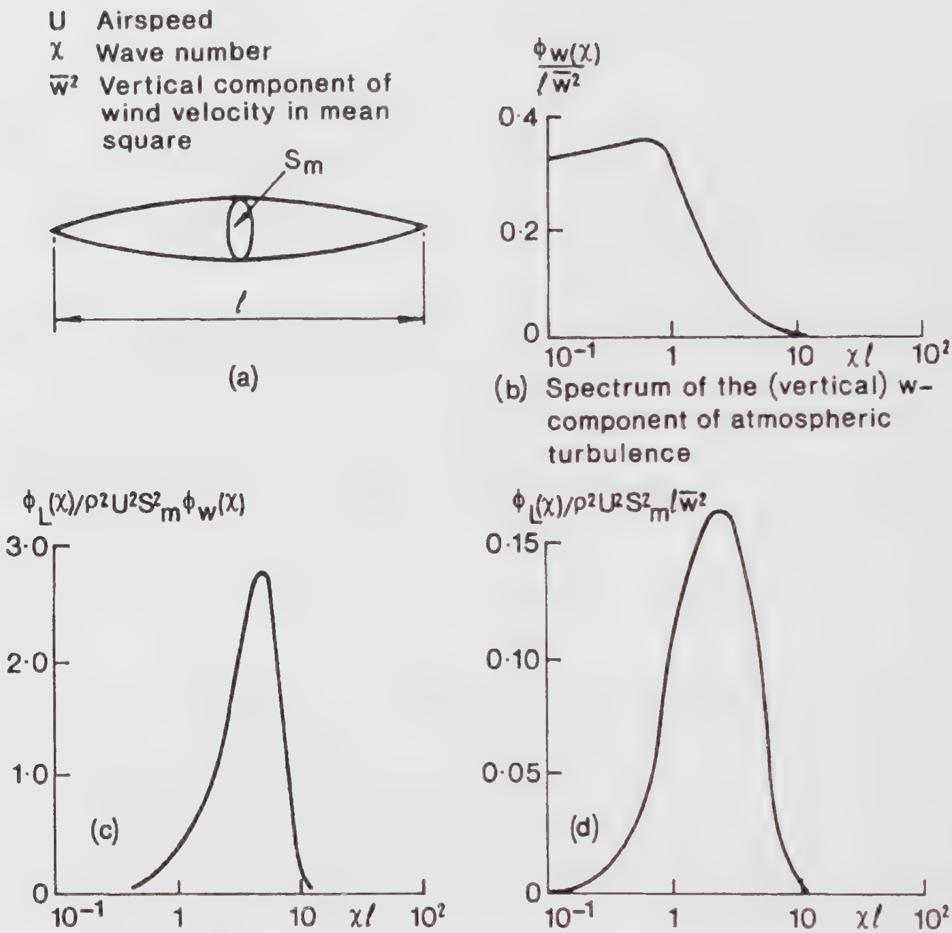
$$S(x) = 16\, S_m\, x^2(1 - x)^2/l^4 \tag{3.31}$$

where: S_m is the maximum value of S. Figure 3.17a shows the body shape.

The vertical component of the turbulent velocity is specified as a spectrum $\Phi(\chi)$ where the wave number $\chi = \omega/U_0$ Figure 3.17b shows this spectrum which is given by:

$$\Phi_w(\chi) = w^2 l(1+3\Omega^2 l^2)/\pi(1+\Omega^2 l^2)^2 \tag{3.32}$$

where: l is the integral scale of turbulence and w^2 the root mean square of the vertical velocity.



Note the sharp peak when the wavelength of the turbulent velocity ($2\pi/\chi$) is equal to l the length of the hull

(c), (d) Spectra of the fluctuating lift on the hull.

With $(\overline{w}^2)^{1/2}$ = 1 m sec^{-1} and U = 30 m sec^{-1}, the lift on the hull in root mean square is 0.06 ½ $\rho U^2 S_m$. The incidence required to produce an equivalent lift in steady flight is more than 3°.

Figure 3.17. The response of an airship hull to atmospheric turbulence.

If l = 330m then the expression fits data recorded during aircraft flights. The spectrum of the lift produced on the hull is given by:

$$\Phi_L(\chi) = \rho^2 U_o^2 \Phi_w(\chi)\, S'(\xi).S'(\eta).\exp\{i\chi\,(\xi-\eta)\}d\xi.d\eta \tag{3.33}$$

where: S' = dS/dx. For the simple body shape in Equation 3.31. Owen evaluated Equation 3.33 analytically. Figure 3.17c shows $\Phi_L(\chi)/\rho^2 U_0^2 \Phi_w(\chi)$ as a function of χl. For the case when l = l the spectra of the fluctuating lift are shown in Figure 3.17d. The airship length was chosen from a project design of Sir Barnes Wallace. If $(w^2)^{1/2}$ = 1 ms^{-1} then the root mean square lift on the hull is $0.06.\frac{1}{2}\rho U_0^2 S_m$, which could also be produced by flying at an incidence of 3°. Figure 3.17c shows that the lift spectrum peaks when the wavelength of the turbulence equals the length of the hull. Owen explained this in Figure 3.18. The vertical velocity from the turbulence changes sign at the centre of the hull. The lift, however, is obtained by multiplying by S', which also changes sign at the hull mid-point. The lift on both halves of the hull is therefore positive. Other turbulent wavelengths will experience some lift cancellation. Any tail surfaces will produce a negative lift in the situation shown in Figure 3.18, which will pitch the airship nose up, so increasing the total lift. The actual gain in lift will depend on the period of the rapid oscillatory mode.

DeLaurier and Hui (1981) use a similar approach but have taken the analysis further by estimating the life of an airship in various weather conditions. Using the method of calculating aerodynamic forces and moments referred to in the section on **Overall Aerodynamic Estimation**, together with Von Karman's model for the turbulence power spectrum (Press and Meadows, 1955) they used values of turbulence scale length l and intensity σ - obtained from flight test data combined with Etkin's (1980) mission analysis technique - and determined various designs' probable lifetimes. This analysis showed the large benefit to vehicle life if the speed is slowed upon entering strong turbulence. This agrees with the habits of Zeppelin captains on encountering strong turbulence, which no doubt contributed to their good flight safety record. DeLaurier and Hui have added a useful weapon to the airship designer's armoury.

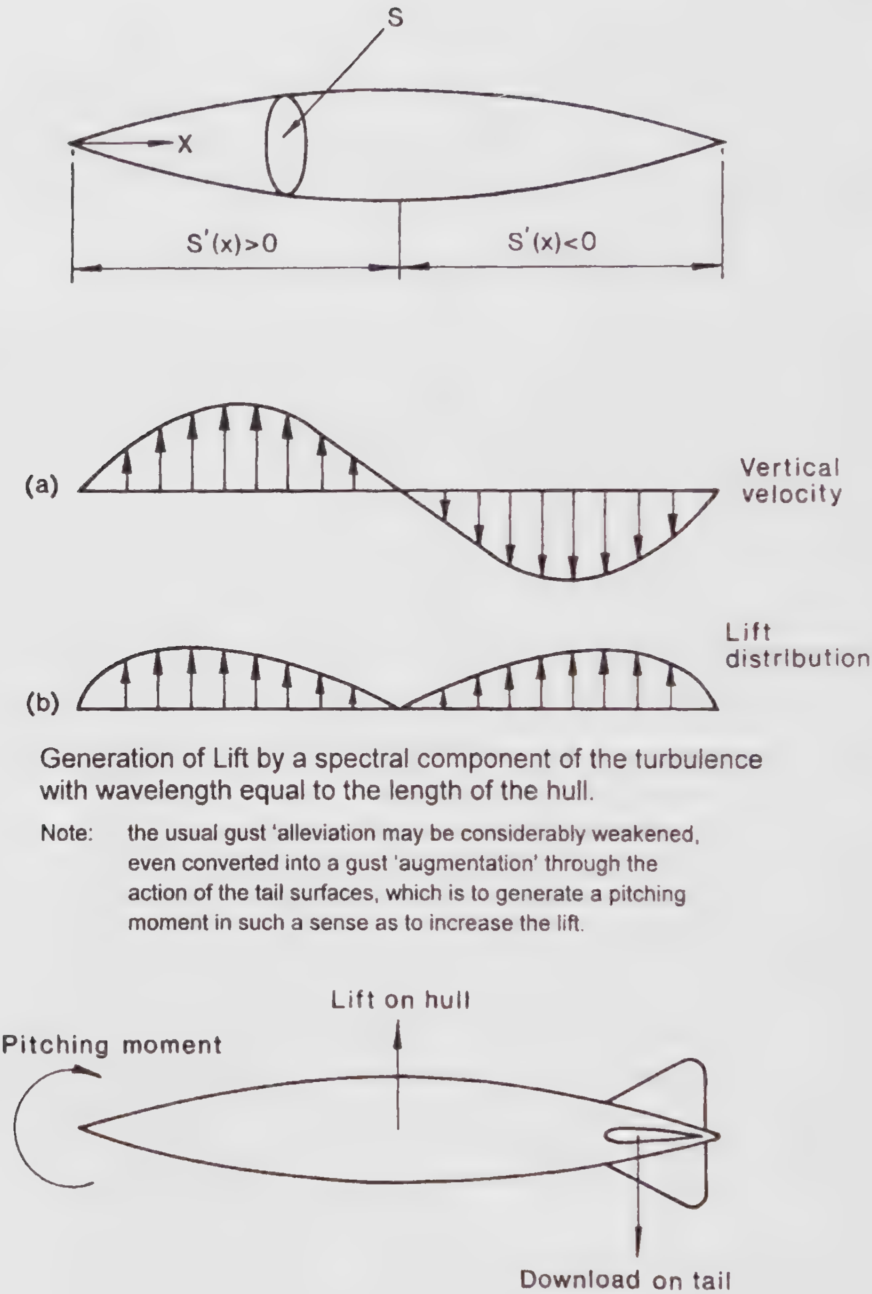


Figure 3.18. Distribution of turbulence induced lift on an airship.

AERODYNAMIC PARAMETER ESTIMATION

Reference has been made above to some of the problems of estimating aerodynamic forces and moments for airships. Calculated results have been compared with wind tunnel and flight measurements. The deduction of forces and moments from flight data is outside the scope of this chapter but wind tunnel testing is discussed. The simple mathematical modelling of the aerodynamics used above is now being complemented by more powerful methods - made possible by the large increase in computer power - which are briefly considered next.

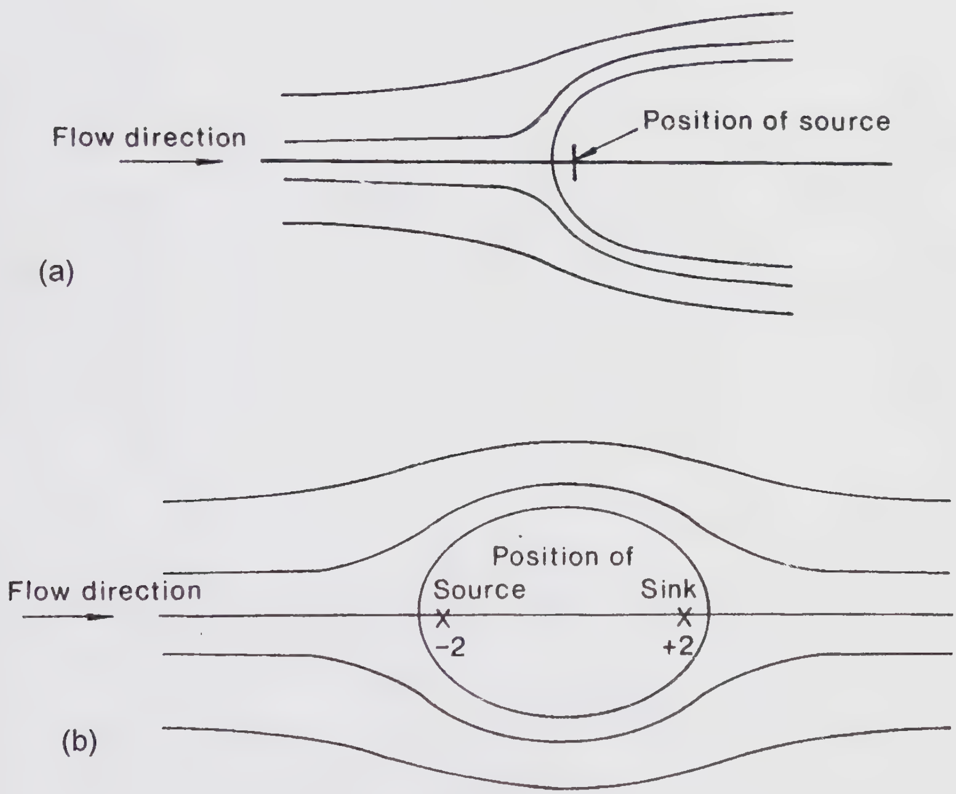


Figure 3.19. (a) Streamline flow about a source in a steady stream.

(b) Streamline flow about a source and a sink in a steady stream.

Computational Fluid Dynamics (CFD)

The use of potential flow models to obtain streamline flows which resemble the shape of the whole or an important part of a body have been referred to earlier. The use of basic fluid dynamic components, namely sinks, sources, doublets and vortices, to obtain the required bounding streamline has been known for more than a century. Excellent descriptions of these methods exist in many text books, for example Milne-Thomson (1955). One simple example for readers unfamiliar with the technique is given next before a more general method is briefly described.

The calculation of the pressure around the nose is important if the designer is to minimise the airship structure weight. A fluid dynamic source placed in a steady flow is a useful starting point. A source is defined as a point from which fluid emerges equally in all directions. The strength of the source, m, is defined as the volume of fluid which emerges per unit time. A sink is a negative source. The streamlines from a source are radii from the point of origin. Applying conservation of volume flow, the velocity at a distance r from the source decreases inversely as the surface area through which the fluid flows. Thus in two-dimensional flow the velocity changes as $1/r$; in three dimensions as $1/r^2$.

A steady stream is represented by parallel streamlines along the flow direction. In inviscid flow new families of streamlines may be generated by the addition of individual streamflows. As a simple two-dimensional example a source of strength m is placed at the origin in a steady stream coming from $-\infty$ parallel to the x axis with velocity V. Figure 3.19a shows some typical streamlines for a value of $m/V = 1$. As flow takes place only along a streamline, a solid frictionless surface may replace any streamline or stream-surface. Curve AA resembles the nose of an airship. Varying the ratio m/V alters the shape, an increase in value making the nose more blunt.

Closed streamline shapes may be produced simply by replacing the source of Figure 3.19a with a source of strength m at $x = -a$ and a sink of strength $-m$ at $x = a$; streamlines are shown in Figure 3.19b for $m/V = 1$ and $a = 2$. Varying m/V and a, allow the thickness ratio of the body to be adjusted. The mathematical expressions of all these flows are known and hence the pressure along any streamline can be computed. The extension of this technique, to model much more complex shapes, was first described by Lamb (1945). The general application of his work has only become feasible with the development of the electronic computer. The shape to be modelled is covered with a lattice. Fluid dynamic sources, sinks, doublets and vortices are arranged within this lattice and the strengths adjusted to give zero flow velocity normal to the surface of the body at certain grid points. The number of grid points is selected to allow the determination of the source and vortex strengths by the solution of the resulting set of simultaneous equations. The accuracy of the approximation increases with the number of grid points. The lattice panels contain a source (sink or doublet) and vortices lie along the edges. Vortex circulation is conserved so, at the trailing edges of the lattice, vortices are shed. As with the fixed-wing aircraft wing tip these vortices extend downstream to infinity. The accuracy of the final solution depends on the skill of the lattice designer as well as the sophistication of the computer program.

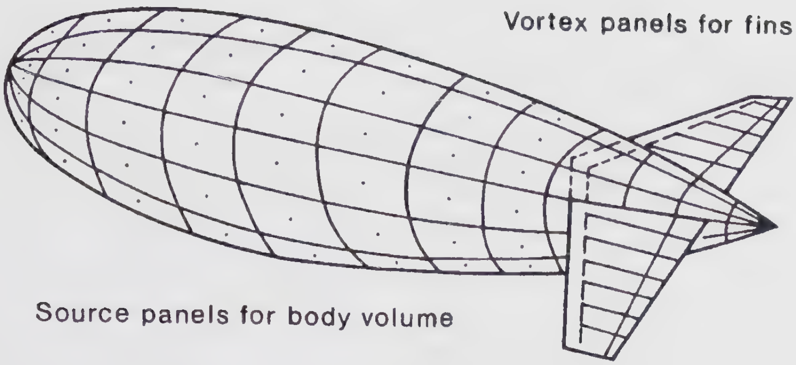


Figure 3.20. Schematic of CFD model of an airship.

Little has been published on the application of these methods to airship problems. The paper by Wong, Zhiyung and Delaurier (1985) is very appropriate. Figure 3.20 shows the general arrangement of the source panels which model the hull and the vortex-lattice panels for the fins. Figure 3.21a shows a source panel and Figure 3.21b the vortex-lattice panels in more detail. The vortex panels continue across the hull to represent the lift carry-over mentioned in the section on **Overall Aerodynamic Estimation**. The fins are assumed to be so thin that no source panels are required to simulate the volume effect.

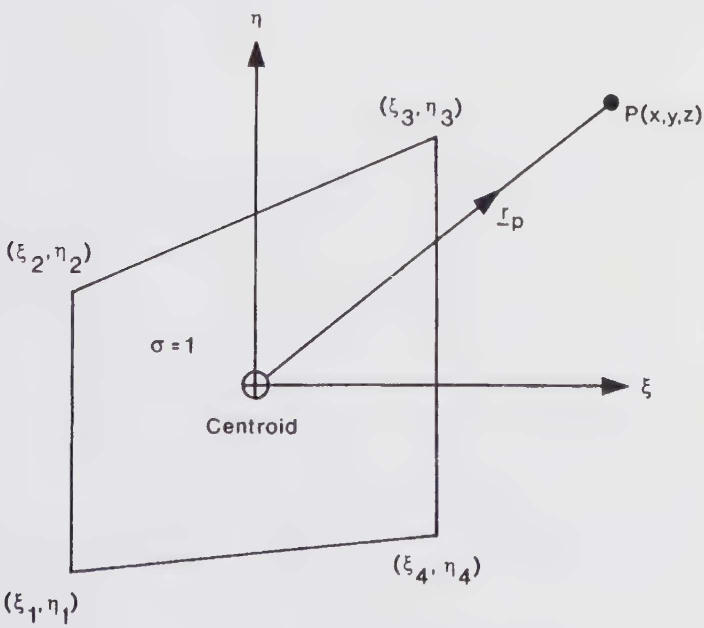


Figure 3.21a. Geometry of a source-panel.

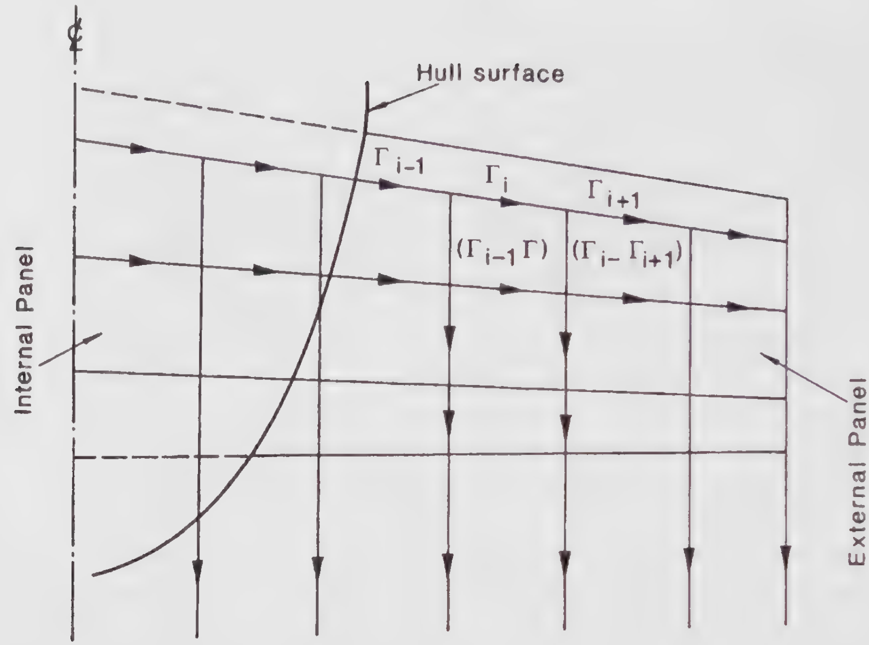


Figure 3.21b. Geometry of a vortex lattice panel.

Figure 3.22 shows a comparison of the results obtained from the isolated hull model (source panels only) with Freeman's (1932) wind tunnel tests of the 'Akron' hull.

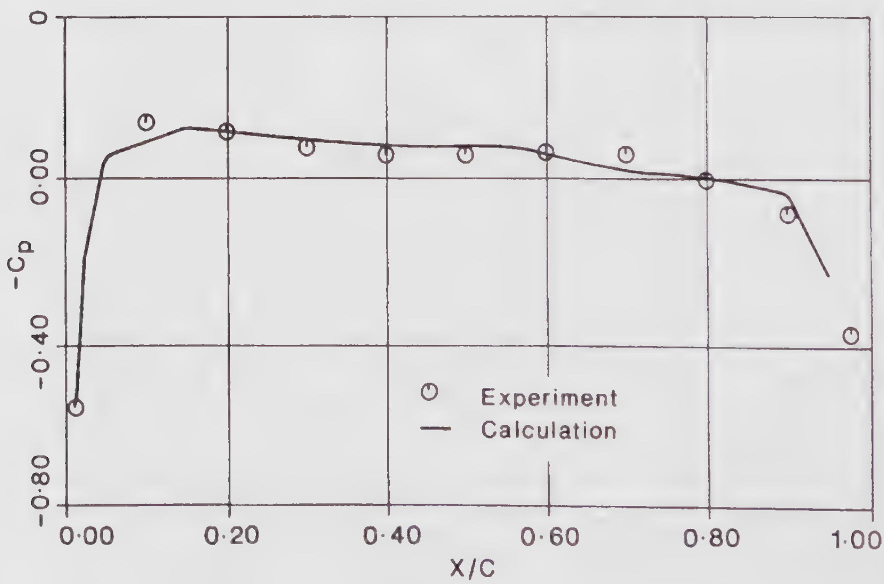


Figure 3.22. CFD and experimental data comparison for an isolated airship hull.

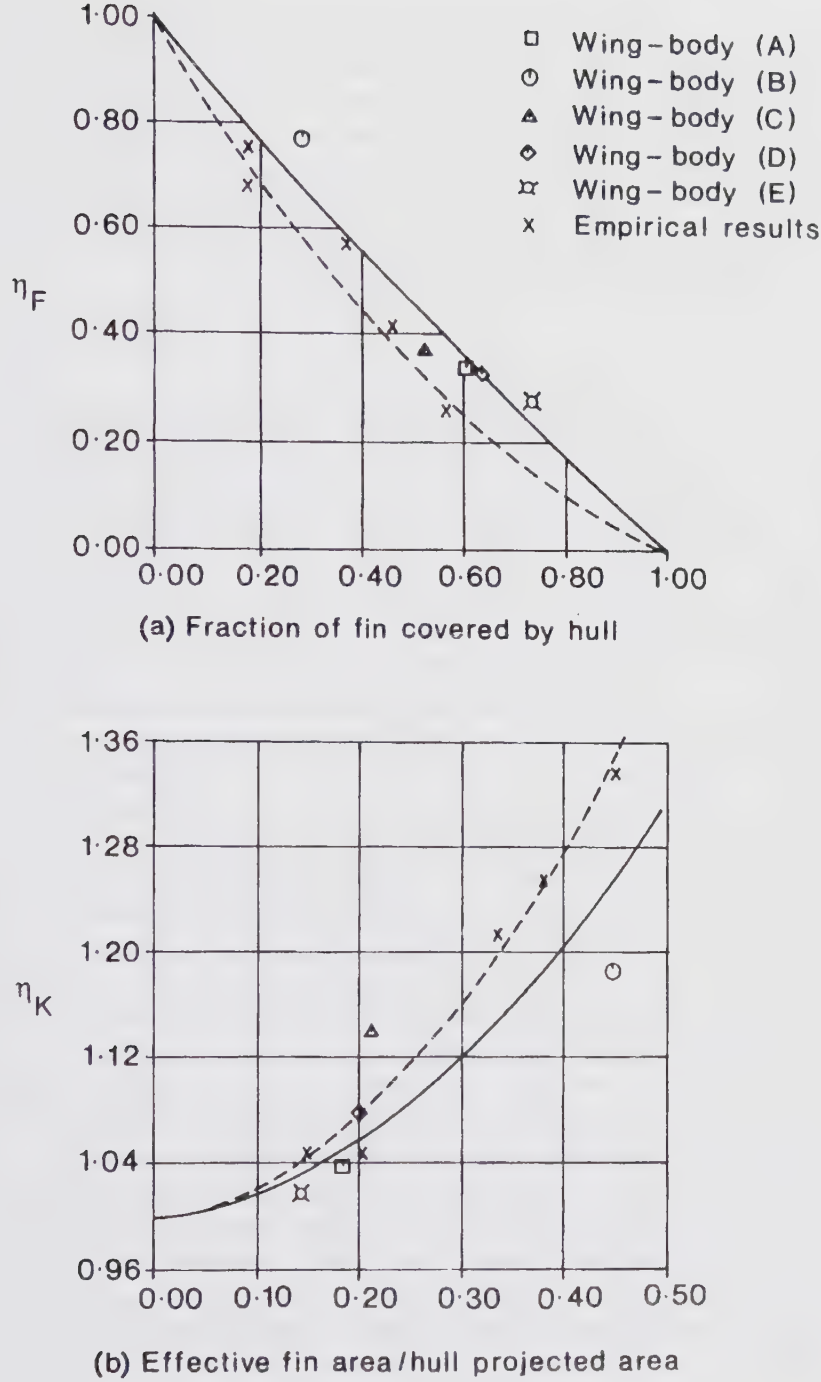


Figure 3.23. Comparison of fin η_f and hull η_k efficiency factors from CFD and experimental data.

Figures 3.23a and 3.23b show the results of applying the full model to five hypothetical airships to calculate the efficiency factors η_k and η_f. These are defined in the section on **Overall Aerodynamic Estimation** and are shown in Figure 3.15 as well as on this Figure. The five designs were produced by adding various fin arrangements to an 'Akron' (ZRS-4) class hull. The curves of Figure 3.15 were empirically deduced from data which included that for the 'Akron'. The agreement is satisfactory and this provides hope that computational fluid dynamics will calculate conditions which have previously relied on empirical estimates.

Wind Tunnel Testing

Wind tunnel tests are performed to answer particular equations. For performance the overall lift, drag and moments of the vehicle in non-turbulent flow are required. Forces and moments from control surfaces provide information to ensure satisfactory handling. Hinge moments from these control surfaces are needed by the control systems engineers. Detailed force distributions are used by the structural design group to optimise the structure. Separately from these tests the response of the vehicle to unsteady flow is required for reasons given in the section on **Unsteady Aerodynamics**. A brief summary of some of the methods and problems associated with such tests is given below. For a more complete discussion of the subject and test results for modern airships, the reader is referred to Gomes (1989a-d and 1990). Gomes (1990) is a summary of the work which is supplemented in the other references.

A basic problem with wind tunnel testing is that the model has to be attached to the tunnel structure. The attachment alters the flow around the model so care must be taken not to affect the critical flow areas. Overall forces and moments of the body may be measured through the attachment, usually through a strain gauge balance recording up to six components. The only technique which does not require a physical attachment is magnetic suspension. The strengths of electro-magnets mounted in the wall of the tunnel are adjusted to hold the model in a fixed attitude and position in the tunnel. Model forces and moments are determined from the magnetic strengths. Most facilities which use this technique are small and, for reasons given in the next section, not suited to airship hull testing. Small force and moment balances may be included in components of the model, e.g. for control surfaces. General distribution of forces on a model are obtained by pressure plotting the surface. Hypodermic tubing is inserted from inside the model to finish flush with the surface. The other end of the tubing is connected to a pressure sensor, which records the static pressure at the surface of the model. Owing to pressure lags in the tubing this technique is only practical for steady flow conditions.

Steady Flow Testing

To ensure that a wind tunnel test reproduces the full scale behaviour certain non-dimensional groups must have the same value for both model and full scale. These groups are determined by dimensional analysis. For steady flow simulation the variables usually considered are fluid velocity V, density ρ and viscosity μ, the speed of sound in the fluid a, the density σ and modulus of elasticity E of the structure, a characteristic length l and gravity g. The non-dimensional groups which have to be maintained are V/a, ρ/σ, $E/\rho V^2$,V^2/lg and $\rho Vl/\mu$. The first group is the Mach, the fourth the Froude and the last the Reynolds number. The simplest wind tunnel uses air at atmospheric pressure and temperature. In this case ρ and μ have the same value at both model and full scale. Only in rigs like whirling arms can apparent gravity be changed so g is constant. It is then easy to show that the model has to be full scale to satisfy the equality of the groups. The choice then lies between the use of a more sophisticated wind tunnel, for example a pressurised or cryogenic facility, or to justify why certain groups are unimportant for the particular tests. For a slow speed vehicle like an airship, Mach number can be ignored as compressibility effects are absent. Since the model need not be buoyant neither ρ/σ nor the Froude number need to be preserved. If $E/\rho V^2$, the ratio of the elastic to the aerodynamic forces is large then a rigid wind tunnel model will be acceptable. This only leaves the Reynolds number to be preserved.

In an atmospheric pressure tunnel preserving Reynolds number means that $V_m l_m = V_f l_f$ where m refers to model and f to full scale. In the Gomes (1989a-d and 1990) work the airship model was 1/75 full scale. So to preserve Reynolds number the tunnel velocity would have had to be 75 times full scale or about 2250 m/s. This would clearly make the neglect of Mach number a major error as well as severely limiting the number of suitable facilities. The Reynolds number is therefore not preserved but other techniques are available to minimise the error. Before discussing these techniques the limits to model size are explored.

The size of the model must be related to the size of the tunnel working section so that the airflow around it approximates that experienced in free flight. If the model is large relative to the size of the tunnel working section then the air velocity around it will be higher than in free flight and the surface pressures lower. The aerodynamic forces and moments will then be in error. Consider the tests made by Gomes (1990) in the Cranfield College of Aeronautics 8x6 foot wind tunnel of 1:75 scale models of a Skyship 600 and the YEZ-2A. For the latter model the maximum cross section is about 3.3% of the tunnel working section area which means an increase in static pressure on that model section of 6.7%. Such an error is acceptable. For models with small thickness ratios, like airship hulls, which require testing at large pitch and/or yaw angles, the model size must be chosen so that neither the nose nor the tail approach close to the tunnel walls. For the YEZ-2A model, yaw and pitch settings up to 30^0 were tested singly and together. For the 6 foot tunnel width the nose or tail of the model was 1.7 feet from the wall at 30^0 which is just acceptable. Airship models with this degree of tunnel blockage are acceptable.

The problem of the wrong Reynolds number remains: model tests were made at 6 x 10^6 when the full scale value was 2.1 x 10^8. The subsections in **Airship Drag** contain many references to the error in skin friction and form drag which wrong Reynolds number will cause. The problems arise due to the different development of the boundary layer. It has long been established that the most important objective is to ensure that the transition from laminar to turbulent boundary layer occurs at about the correct position on the model. This is done by 'tripping' the boundary layer usually with some added surface roughness. This will change the skin friction coefficient of the body but preserve the form drag and lift. In the subsection, ***The Bare Hull***, it was shown that skin friction drag dominated the hull drag so drag results from roughened models may be in significant error. Gomes (1989a and 1990) went to considerable trouble to ensure that his tests, which have been quoted throughout this chapter, were as realistic as possible. For pilot tests on the Skyship 600 model he covered the model with fishnet or fine mesh human stocking material. The fine mesh stocking suppressed early flow separations but, because it raised the skin friction coefficient, the drag exceeded a full scale value by 60%. Fine tuning the roughness would therefore be necessary to obtain accurate drag figures. For the YEZ-2A model Gomes decided that it was impractical to use stockings owing to the size of the model. He therefore obtained the required degree of surface roughness by spraying the polyurethane hull with a grey paint from a distance of approximately 60cms. This gave a coarse roughness "*which was felt to closely reproduce the fine mesh stocking type of surface roughness*" used for the Skyship 600 tests.

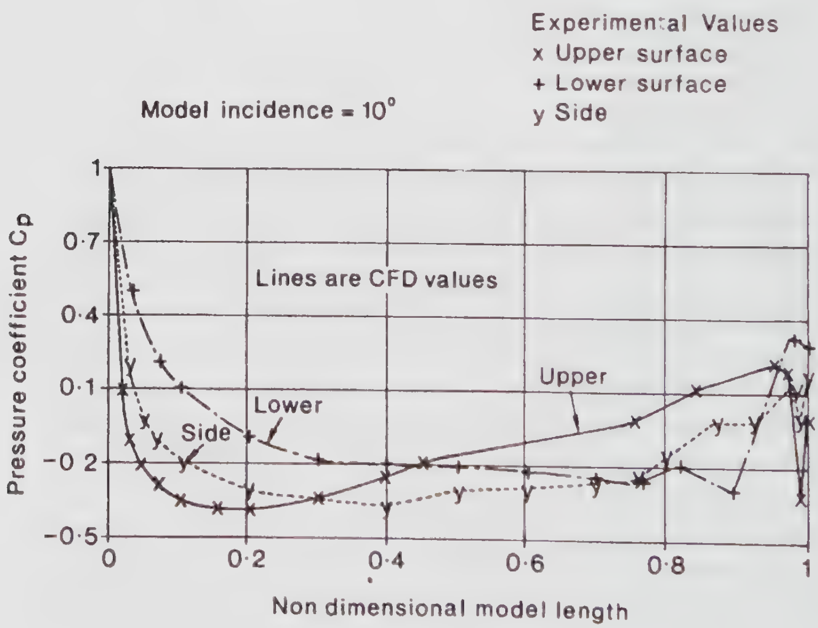


Figure 3.24. Comparison of CFD calculations & wind tunnel results for 1/75 scale Skyship 600 model.

The YEZ-2A test programme run by Gomes produced approximately 1,700 whole model force and moment coefficient data points, pressure distribution data from 96 pressure tappings around the hull and along the quarter chord line of some of the fins, control surface hinge deflection moments obtained from strain gauge balances fitted to their deflection axes and some flow visualisation. The need to obtain pressure distributions places a further condition on the surface roughness which can be used. If the flow path to the flush mounted pressure tapping is obstructed so that the flow either separates over the hole or alternatively produces an eddy that directs flow into the hole, an erroneous reading will be obtained. Pressure distributions from this work are shown in Figures 3.5 and 3.6.

Figure 3.24 copied from Gomes (1989a) shows the pressure distribution around a Skyship 600 at 10^0 incidence. The continuous curves are CFD calculations made independently. This is one of the very few published comparisons where the tunnel testing and the CFD calculation are at comparable states of development. The agreement is good.

Unsteady Flow Testing

Some difficulties that airships have encountered in turbulence have been referred to in the previous section on **Unsteady Aerodynamics**. Some computational work on this problem was discussed. The advantages of having an independent assessment of the airship response before first flight are obvious.

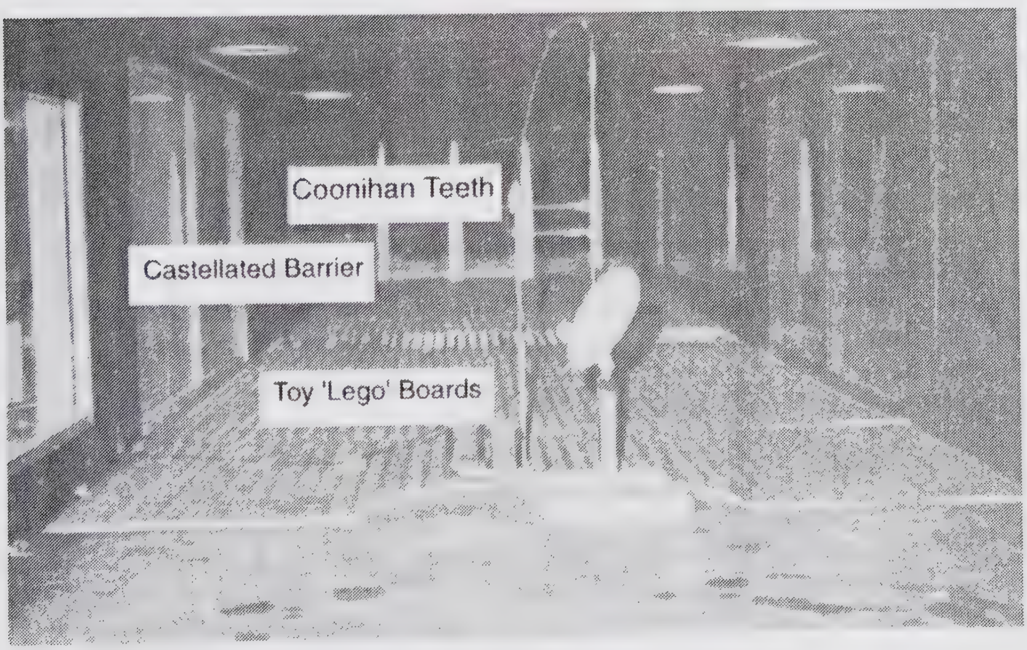


Figure 3.25. Airship model in Cranfield 8 x 4 foot boundary layer wind tunnel.

Traditionally wind tunnel designers have made great efforts to minimise turbulence in the working section. As a consequence of structural failure of buildings owing to atmospheric turbulence, methods have been developed that produce a prescribed velocity gradient and turbulence spectrum in a wind tunnel working section. The technique is to place obstructions upstream of the model to generate controlled velocity defect and scaled turbulence. Figure 3.25 shows the complete installation in the Cranfield wind tunnel. Three forms of obstruction can be identified. In the far end of the tunnel a (white) castellated barrier is behind the tall (brown) Counihan teeth. Finally small (red) toy 'Lego' boards are carefully distributed ahead of the model. Further information on the design and calibration of the scale of turbulence may be found in Cook (1987 and 1988). This is a 1/200th scale model of the YEZ-2A mounted on a vertical support through a strain gauge balance in the model interior which measured forces and moments about the model centre of volume. The body-size must be chosen to have the same relation with the tunnel-induced turbulence as the full scale airship has to atmospheric turbulence. In order that the turbulence-induced forces on the body could be measured, the body had to be very light. Since it was small the Reynolds number was low and the boundary layer had to be tripped. This was done by covering it with a fine mesh stocking as described in the previous subsection on *Steady Flow Testing*.

The vertical and fore and aft turbulent velocities were measured by a hot wire anemometer situated 1.5 maximum model diameters ahead of the nose. This provided information on the forcing function. The response of the body, measured by the strain gauge balances, was recorded simultaneously. The data were analysed to determine the force and pitching moment response to the different turbulence frequencies. Gomes limited his published analysis to the lift and pitching moment response to the vertical, w, turbulent velocity. The results were presented as three graphs for each test condition. The transfer function, which is the ratio of the power spectral density of the output (lift or pitching moment in this case) to the power spectral density of the input (here the w-velocity component) as a function of the wave number Ω, defined in the previous section on **Unsteady Aerodynamics**. The peaks indicate the value at which the lift or moment response is greatest.

Unfortunately the peaks may not all be due to the w-velocity component. Peaks may also arise from the u- and v-velocity components of the turbulence as well as from resonances in the model strain gauge balance assembly. Care was taken to identify the latter effects by careful design and in proving tests.

By calculating the phase angle between input and output and their coherence at each Ω the importance of each peak was assessed. If a peak in the transfer function is accompanied by a marked phase shift at about the same Ω this makes it more likely that the response is due to the input function. The coherence measures the correlation between the input and output and varies from 0 to 100%, the latter figure representing perfect correlation. An example from Gomes (1989e) work is shown in Figure 3.26 for lift response of the body and fins combination. Gomes's analysis of these curves is given in Table 3.6.

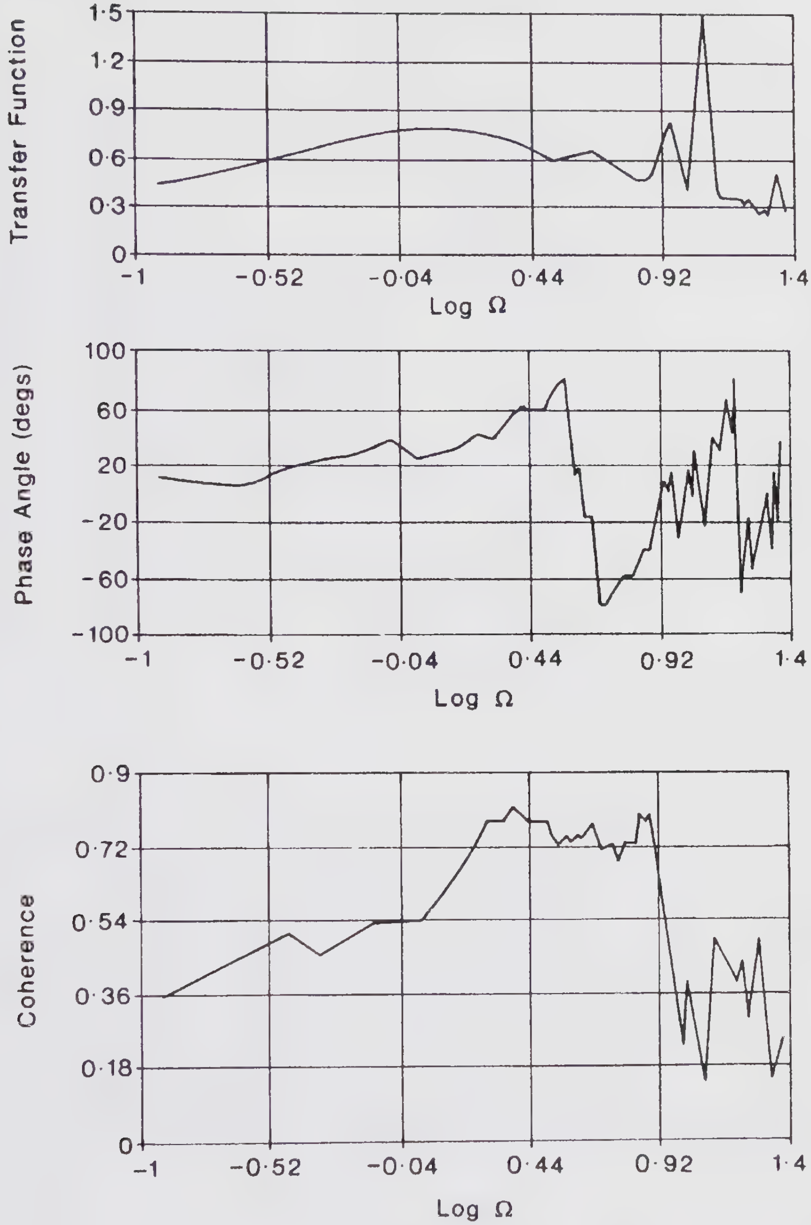


Figure 3.26. Transfer function, phase angle and coherence vs. log (wave no.) for lift with turbulent vertical velocity at zero pitch and yaw.

The value of this class of experiments is clear. Coupled with analysis such as that described in the previous section on **Unsteady Aerodynamics**, it provides the airship designer with important aerodynamic data.

Table 3.6. *Summary of response of turbulence results for 0^0 of yaw and pitch*

Interval of High Coherence	Peaks in the Transfer Function	Comments
	$\Omega = 5\ m^{-1}$ $\lambda = 2L$	Accompanied by a sharp phase shift. The most important single result.
$\Omega = 1.8$ to $8\ m^{-1}$ $\lambda = 5.4$ to $1.2L$	$\Omega = 8.9\ m^{-1}$ $\lambda = 1.1L$ $\Omega = 11.5 m^{-1}$ $\lambda = 0.9L$	Both occur in region of low coherence and therefore probably not due to w velocity

Ω = Turbulence Wave No.
λ = Turbulence Wave Length
L = Airship Model Length

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4

Stability and Control

M.V. Cook

INTRODUCTION

The fundamental airframe stability, control and dynamic characteristics of the modern airship are not significantly different from those of the earliest airships. For example, the analysis by Bairstow (1920) is as valid today as it was in 1920. It is, however, more readily apparent that the technology of the modern airship differs substantially from that of earlier counterparts, and it is the technology difference which is potentially most likely to introduce detail differences in stability and control characteristics. In the present context, perhaps the most significant developments include envelope shape and stiffness, mechanisms for control and propulsion and electronic flight control systems (EFCS).

Early airships were either of the classical rigid shape, which was usually cylindrical in form, or non-rigid of prolate ellipsoid form, both types generally having a high fineness ratio. By comparison, modern airships, irrespective of size, have been primarily non-rigid, more ellipsoid in form and have a lower fineness ratio. Modern envelope materials probably improve aerodynamic cleanness combined with adequate stiffness and light weight. Modern methods for estimating and measuring the aerodynamic properties of the airship are superior and, although the aerodynamic properties are unlikely to have changed much over the years, today they can be more accurately estimated leading in turn to a better description of stability and control characteristics.

What has not improved very much is the provision of aerodynamic stability and control. Fin size, and hence dynamic damping and weathercock stability, is limited. Generally, low speeds demand large fin sizes for aerodynamic effectiveness but this is impractical as the fin structure has to be entirely supported by the fabric envelope and, furthermore, manoeuvre loads generated by control surface deflection have to be applied to the envelope without causing it to collapse. Consequently, practical fins and control surfaces are of low aspect ratio and tend to be substantially immersed in the forebody wake, aerodynamic efficiency is therefore not very high. In the past long mechanical control runs and significant structural flexibility have produced high levels of lost motion and hence exacerbated poor control effectiveness. Today, fly-by-wire (FBW) or fly-by-light (FBL) control systems signalling actuators mounted in the control surfaces have contributed to some improvement in aerodynamic control effectiveness.

Without a doubt the most dramatic contribution to the development of the stability, control and dynamics of the modern airship stems from developments in computer technology. It is now perfectly feasible to undertake hitherto difficult, if not impossible, analysis and simulation which has enabled the attainment of new levels of insight and understanding. This in turn has encouraged the development of more detailed and more accurate aerodynamic and dynamic models of the airship culminating in extremely comprehensive non-linear simulation models such as that developed by Gomes (1990). The digital computer is now also firmly established for the control of air vehicles and is the nucleus of the EFCS, which can be used to very good effect in the airship. It enables the characteristics and effectiveness of the primary flying controls to be precisely determined at all flight conditions, it enables stability augmentation for improved flying qualities, it enables automatic pilot functions and navigation modes and, with further development, it may enable handling qualities to be more precisely determined. The euphoria, however, is tempered when it is realised that the performance of the EFCS is limited by the effectiveness of the aerodynamic control surfaces it drives. New developments may overcome this limitation to a certain extent by integrating control of the propulsion unit thrust vectoring into the overall control strategy.

Any scientific investigation of the stability and control of the airship requires a mathematical model built around the equations of motion and, it is important that the detail of the model is appropriate to the kind of investigation anticipated. In the first instance, however, it is also important that the model is not so detailed that it obscures the fundamental factors which determine the basic dynamic properties of the airship. A relatively simple linear model is readily analysed and fosters the essential understanding since 'dynamic visibility' tends to be good. Having achieved this it is then a relatively straightforward matter to develop the model into a more detailed non-linear simulation model whose basic stability and control properties are well understood.

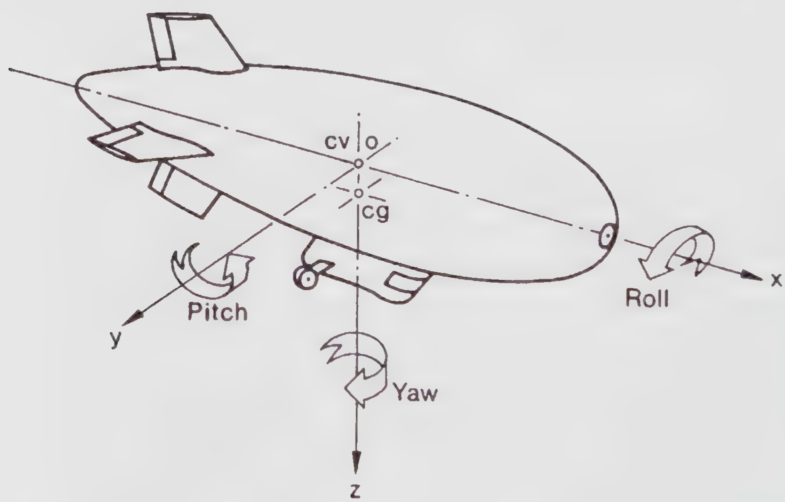

Figure 4.1. General configuration body axes.

SYSTEM OF AXES AND NOTATION

As in typical aircraft practice it is convenient to define a right handed orthogonal axis system fixed in the airship and constrained to move with it. For the purposes of studying the dynamics, stability and control of the airship the motion of the axes is considered with respect to an initial condition, which is usually, but not necessarily, trimmed equilibrium flight. General configuration body axes are shown in Figure 4.1 and are most conveniently fixed in the vehicle with the origin *o* at the centre of volume (cv), the *ox* axis is coincident with the axis of symmetry of the envelope and the *oxz* plane coincides with the longitudinal plane of symmetry of the airship. Since the volume of the gondola is negligible compared with that of the envelope it is reasonable to assume that the cv lies on the axis of symmetry of the envelope.

Rectilinear Flight

The typical axis notation corresponding with trimmed steady rectilinear flight is shown in Figure 4.2. The total speed and body attitude are denoted V_o and θ_e respectively. The buoyancy force *B* acts at the centre of buoyancy (cb), which has co-ordinates (b_x, b_y, b_z) and the weight acts at the centre of gravity (cg) which has co-ordinates (a_x, a_y, a_z). The total engine thrust T_o acts at a point below the *ox* axis but its precise location depends on the geometry of the installed propulsion system.

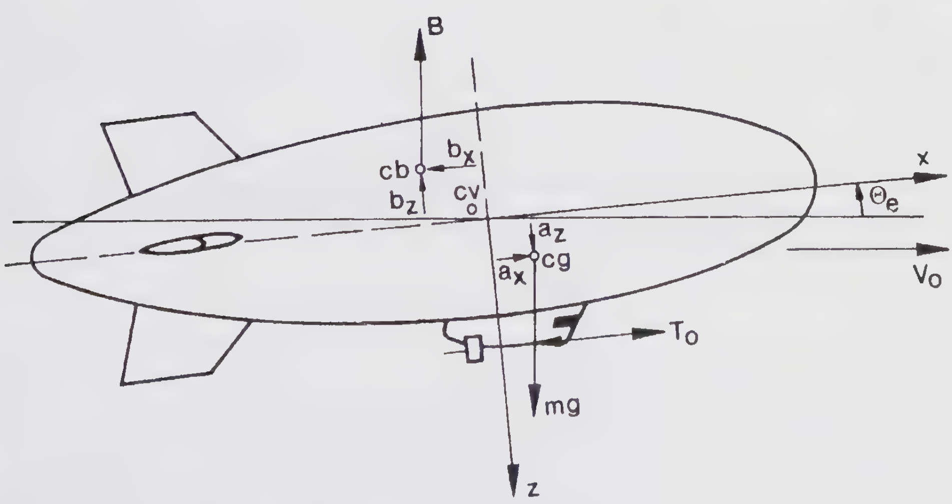

Figure 4.2. Trimmed axes notation.

In steady flight the total velocity V_o resolves into three components U_e, V_e, W_e and,

$$Vo \;=\; (U_e + V_e + W_e)^{0.5} \tag{4.1}$$

In disturbed flight the corresponding velocity components become,

$$U = u + U_e \qquad V = v + V_e \qquad W = w + W_e \tag{4.2}$$

where, u,v,w and p,q,r are the perturbation components of linear and angular velocities respectively with respect to trimmed equilibrium. Thus, in undisturbed flight these perturbation variables and their derivatives are all zero.

In order to develop a meaningful mathematical model of the airship it is first necessary to make some assumptions which constrain the problem to practical bounds and which help to provide dynamic visibility by reducing the equations of motion to a reasonably simple level. The assumptions are;

- The familiar aircraft dynamic modelling methods apply.
- Steady low speed rectilinear flight is assumed.
- A stationary atmosphere is assumed.
- Motion is described as a perturbation, not necessarily small, about an initial trimmed flight condition.
- The mass of the airship remains constant.
- Rigid body motion only is considered, aeroelastic effects are omitted.
- The airship is symmetric about the oxz plane and both cb and cg lie in that plane such that $a_y = b_y = 0$.
- The layout of the airship is classical. It has four mutually perpendicular rear fin surfaces each incorporating an aerodynamic flap type control surface and, it has two independently controlled thrust vectoring propulsion units mounted either side of the aft end of the gondola.

THE EQUATIONS OF MOTION

The development of the equations of motion follows standard aircraft practice where derivative notation is used to describe aerodynamic effects. The major differences are due to the fact that the vehicle is buoyant and displaces a large volume. The buoyancy force B and virtual mass and inertia terms are significant additions to the familiar aircraft equations of motion. A comprehensive mathematical model for a body immersed in a fluid was developed by Lewis, Lipscombe &

Thomasson (1984) for use in computer simulation, this model has been adapted for the airship application by Cook (1990) which provides the basis for the present description.

The virtual mass and inertia effects are described by the derivatives of aerodynamic force and moment with respect to linear and angular acceleration perturbations. For this reason it is arguable whether these effects should be regarded as part of the aerodynamic description of the model or whether they should be regarded literally as additional mass or inertia terms. In the present context the latter description is preferred since in a practical situation it is impossible to distinguish between physical mass and inertia and added mass and inertia.

As an illustration, consider the component of axial force owing to virtual mass effects in a linear axial acceleration perturbation $\dot{U}$,

$$\text{axial force component } = \frac{\partial X}{\partial \dot{U}}\dot{U} \equiv \mathring{X}_{\dot{u}}\dot{U} \tag{4.3}$$

where, $\mathring{X}_{\dot{u}}$ is the dimensional derivative symbol, is typically negative in value and clearly has the units of mass. Thus $\mathring{X}_{\dot{u}}$ and similar terms may simply be added to the physical mass and inertia terms in the development of the equations of motion; whence the following may be defined:

Components of apparent mass.

$$m_x = m - \mathring{X}_{\dot{u}} \qquad m_y = m - \mathring{Y}_{\dot{v}} \qquad m_z = m - \mathring{Z}_{\dot{w}} \tag{4.4}$$

Apparent moments of inertia.

$$J_x = I_x - \mathring{L}_{\dot{p}} \qquad J_y = I_y - \mathring{M}_{\dot{q}} \qquad J_z = I_z - \mathring{N}_{\dot{r}} \tag{4.5}$$

Apparent products of inertia.

$$\begin{aligned} J_{xy} &= I_{xy} + \mathring{L}_{\dot{q}} \equiv I_{xy} + \mathring{M}_{\dot{p}} \\ J_{xz} &= I_{xz} + \mathring{N}_{\dot{p}} \equiv I_{xz} + \mathring{L}_{\dot{r}} \\ J_{yz} &= I_{yz} + \mathring{M}_{\dot{r}} \equiv I_{yz} + \mathring{N}_{\dot{q}} \end{aligned} \tag{4.6}$$

Now, since the airship is symmetric about the *oxz* plane then,

$$J_{xy} = J_{yz} = 0 \tag{4.7}$$

The six degrees of freedom equations of motion may be developed by realising Newton's second law of motion for each degree of freedom in turn. Simplifications resulting from the assumption that the airship is symmetric are incorporated.

The force equations may therefore be written,

Axial force:

$$\begin{aligned} &m_x \dot{U} + \left(ma_z - \overset{\circ}{X}_{\dot{q}}\right)\dot{q} + m_z qW - m_y rV - \\ &ma_x\left(q^2 + r^2\right) - ma_z pr = X_a + X_b + X_g + X_c + X_p \end{aligned} \tag{4.8}$$

Side force:

$$\begin{aligned} &m_y\dot{V} - \left(ma_z + \overset{\circ}{Y}_{\dot{p}}\right)\dot{p} + \left(ma_x - \overset{\circ}{Y}_{\dot{r}}\right)\dot{r} + m_x rU - m_z pW + \\ &ma_x pq + ma_z qr = Y_a + Y_b + Y_g + Y_c + Y_p \end{aligned} \tag{4.9}$$

Normal force:

$$\begin{aligned} &m_z\dot{W} - \left(ma_x + \overset{\circ}{Z}_{\dot{q}}\right)\dot{q} + m_y pV - m_x qU + ma_x pr - \\ &ma_z\left(p^2 + q^2\right) = Z_a + Z_b + Z_g + Z_c + Z_p \end{aligned} \tag{4.10}$$

The corresponding moment equations may be written,

Rolling moment:

$$\begin{aligned} &J_x\dot{p} - \left(J_y - J_z\right)qr - J_{xz}\left(\dot{r} + pq\right) - \left(ma_z + \overset{\circ}{L}_{\dot{v}}\right)\dot{V} - \\ &ma_z\left(rU - pW\right) = L_a + L_b + L_g + L_c + L_p \end{aligned} \tag{4.11}$$

Pitching moment:

$$
\begin{aligned}
&J_y\dot{q} + (J_x - J_z)pr - J_{xz}\left(r^2 - p^2\right) + \left(ma_z - \mathring{M}_{\dot{u}}\right)\dot{U} - \\
&\left(ma_x + \mathring{M}_{\dot{w}}\right)\dot{W} - ma_x(pV - qU) + ma_z(qW - rV) \quad = \\
&M_a + M_b + M_g + M_c + M_p
\end{aligned}
\tag{4.12}
$$

Yawing moment:

$$
\begin{aligned}
&J_z\dot{r} - \left(J_x - J_y\right)pq - J_{xz}(\dot{p} - pr) + \left(ma_x - \mathring{N}_{\dot{v}}\right)\dot{V} + \\
&ma_x(rU - pW) = N_a + N_b + N_g + N_c + N_p
\end{aligned}
\tag{4.13}
$$

Terms on the right hand side (RHS) of the equations are components of force or moment due to aerodynamic effects, static buoyancy, gravitational force, aerodynamic controls and propulsion respectively. At this stage the model can be extended as required by the addition of further terms on the RHS of the equations of motion, for example, force and moment components due to atmospheric disturbances.

The aerodynamic force and moment components may be expressed in the usual dimensional derivative notation as functions of the perturbation variables U,V,W and p,q,r, for example,

$$
\begin{aligned}
&X_a = \mathring{X}_u U + \mathring{X}_v V + \mathring{X}_w W + \mathring{X}_p p + \mathring{X}_q q + \mathring{X}_r r = \\
&\mathring{X}_u U_e + \mathring{X}_u V_e + \mathring{X}_w W_e + \mathring{X}_u u + \mathring{X}_v v + \mathring{X}_w w + \\
&\mathring{X}_p p + \mathring{X}_q q + \mathring{X}_r r
\end{aligned}
\tag{4.14}
$$

or,

$$
X_a = X_e + \mathring{X}_u u + \mathring{X}_v v + \mathring{X}_w w + \mathring{X}_p p + \mathring{X}_q q + \mathring{X}_r r \tag{4.15}
$$

where X_e is the trim equilibrium component of axial aerodynamic force and the remaining terms are dynamic terms which are non-zero only during a perturbation. The aerodynamic components in the other equations may be similarly defined.

Since both the gravitational force mg and the buoyancy force B are static they may conveniently be treated together in the interests of simplicity. The components of force and moment arising from the static forces results from the attitude perturbation of the airship. Denoting the attitude disturbance of the airship ϕ,θ,ψ in the usual way then, the force and moment components may be derived by resolving mg and B from earth axes into disturbed airship axes using the standard direction cosines. Whence,

$$\begin{aligned}
X_b + X_g &= -(mg - B)\sin(\theta + \theta_e) \\
Y_b + Y_g &= (mg - B)\sin\phi\cos(\theta + \theta_e) \\
Z_b + Z_g &= (mg - B)\cos\phi\cos(\theta + \theta_e) \\
L_b + L_g &= -(mga_z + Bb_z)\sin\phi\cos(\theta + \theta_e) \\
M_b + M_g &= -(mga_z + Bb_z)\sin(\theta + \theta_e) - \\
&\qquad (mga_x + Bb_x)\cos\phi\cos(\theta + \theta_e) \\
N_b + N_g &= (mga_x + Bb_x)\sin\phi\cos(\theta + \theta_e)
\end{aligned} \tag{4.16}$$

The aerodynamic control surfaces notation is shown on Figure 4.3 and it is assumed that the vertical surfaces are synchronised to operate like a conventional rudder and, the horizontal surfaces are similarly synchronised to operate like a conventional elevator. Since it appears to be typical it is assumed that there is no provision for aerodynamic control of roll. Let the elevator and rudder surface deflection angles be δ_e and δ_r respectively the positive sense being conventional as indicated on Figure 4.3.

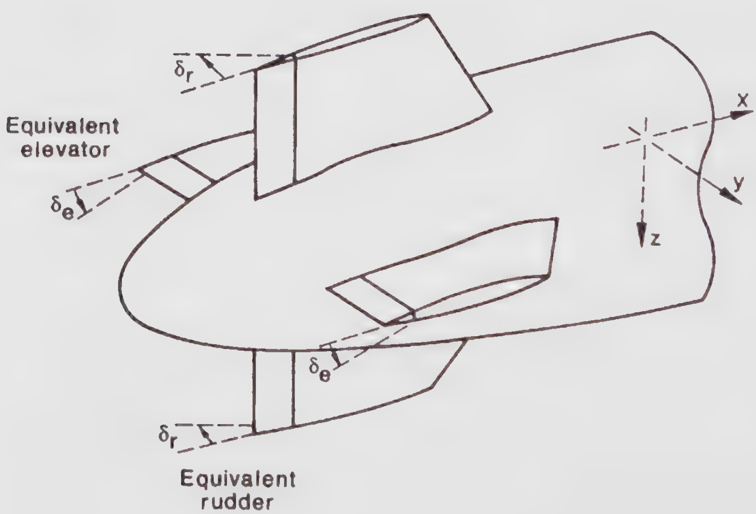

Figure 4.3. Control surfaces notation.

The components of aerodynamic control force and moment may then be expressed in terms of dimensional control derivatives as follows,

$$
\begin{aligned}
X_c &= \overset{\circ}{X}_\delta(\delta_e + \delta_r) \qquad & L_c &= 0 \\
Y_c &= \overset{\circ}{Y}_\delta\, \delta_r & M_c &= \overset{\circ}{M}_\delta\, \delta_e \\
Z_c &= \overset{\circ}{Z}_\delta\, \delta_e & N_c &= \overset{\circ}{N}_\delta\, \delta_r
\end{aligned}
\tag{4.17}
$$

Since geometric and aerodynamic symmetry are assumed then,

$$\overset{\circ}{Y}_\delta = \overset{\circ}{Z}_\delta \qquad \text{and} \qquad \overset{\circ}{M}_\delta = \overset{\circ}{N}_\delta \tag{4.18}$$

and for convenience trim equilibrium is assumed to correspond with the condition $\delta_e = \delta_r = 0$. This may not always be the case, in particular δ_e may be set at a non-zero value to trim. Clearly it is then a straightforward matter to change the description of the aerodynamic controls components to reflect the control strategy adopted. Generally the derivative $\overset{\circ}{X}_\delta$ would be omitted since it is a measure of the increase in drag due to control surface deflection which is likely to be insignificantly small.

A typical propulsion system geometry is shown on Figure 4.4 and assumes two ducted fan thrust units symmetrically mounted at the aft of the gondola.

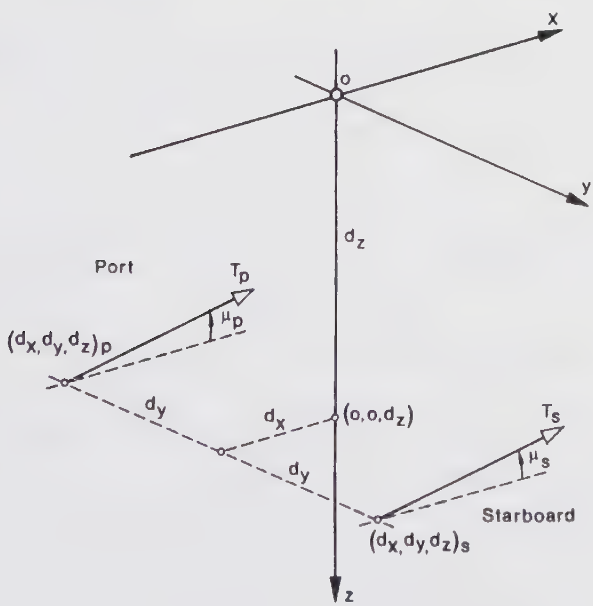

Figure 4.4. Typical propulsion system geometry.

The co-ordinates of the points of action of the thrust are (d_x, d_y, d_z) and it is assumed that thrust magnitude T and direction μ in the pitch plane are independently variable. Then,

$$\begin{aligned} X_p &= T_s \cos\mu_s + T_p \cos\mu_p \\ L_p &= \left(T_p \sin\mu_p - T_s \sin\mu_s\right)d_y \\ Y_p &= 0 \\ M_p &= T_p\left(d_z \cos\mu_p - d_x \sin\mu_p\right) + \\ &\quad T_s\left(d_z \cos\mu_s - d_x \sin\mu_s\right) \\ Z_p &= -T_s \sin\mu_s - T_p \sin\mu_p \\ N_p &= \left(T_p \cos\mu_p - T_s \cos\mu_s\right)d_y \end{aligned} \tag{4.19}$$

For normal flight it is assumed that thrust is controlled symmetrically and synchronously such that the port and starboard contributions are equal in every respect, thus writing,

$$\begin{aligned} T_p + T_s &= T_0 \\ \mu_p + \mu_s &= 0 \\ T_p &= T_s \end{aligned} \tag{4.20}$$

then,

$$\begin{aligned} Y_p = Z_p = L_p = N_p &= 0 \\ X_p &= T_0 \\ M_p &= T_0 d_z \end{aligned} \tag{4.21}$$

or, alternatively, in derivative notation,

$$X_p = T_e + \mathring{X}_t\,\delta_t \quad \text{and} \quad M_p = T_e d_z + \mathring{M}_t\,\delta_t \tag{4.22}$$

where, for example, T_e is the trimmed equilibrium thrust and δ_t is the synchronised throttle lever angle 'perturbation' about the trim setting.

The Equations of motion 4.8 to 4.22 may be assembled together to describe the fully coupled dynamic behaviour of the airship. This model would be most appropriate for computer simulation but is not very amenable to mathematical analysis, this is more readily accomplished with a linearised small perturbation model.

THE LINEARISED EQUATIONS OF MOTION

When it is assumed that motion of the airship is constrained to small perturbations about the trimmed equilibrium flight condition then the model - described in the previous section - may be considerably simplified. In particular, the products and squares of small perturbation variables u,v,w and p,q,r become negligibly small and since the attitude perturbations ϕ,θ,ψ are also small, their sines and cosines may take small angle approximations. In small perturbations it is also reasonable to assume decoupled longitudinal and lateral motion and consequently all coupling derivatives may be omitted from the equations.

Longitudinal Equations

The linearised longitudinal decoupled equations of motion may therefore be written;

$$m_x\dot{u} + \left(ma_z - \overset{\circ}{X}_{\dot{q}}\right)\dot{q} =$$

$$\left\{\begin{array}{l} X_e + \overset{\circ}{X}_u u + \overset{\circ}{X}_w w + \left(\overset{\circ}{X}_q - m_z W_e\right)q + \overset{\circ}{X}_\delta(\delta_e + \delta_r) \\ + \overset{\circ}{X}_t \delta_t + T_e - (mg - B)(\sin\theta_e + \theta\cos\theta_e) \end{array}\right\}$$

$$m_z\dot{w} - \left(ma_x + \overset{\circ}{Z}_{\dot{q}}\right)\dot{q} =$$

$$\left\{\begin{array}{l} Z_e + \overset{\circ}{Z}_u u + \overset{\circ}{Z}_w w + \left(\overset{\circ}{Z}_q + m_x U_e\right)q + \overset{\circ}{Z}_\delta \delta_e \\ +(mg - B)(\cos\theta_e - \theta\sin\theta_e) \end{array}\right\}$$

$$J_y\dot{q}+\left(ma_z-\overset{\circ}{M}_{\dot{u}}\right)\dot{u}-\left(ma_x+\overset{\circ}{M}_{\dot{w}}\right)\dot{w}=$$

$$\left\{\begin{matrix} M_e+\overset{\circ}{M}_u u+\overset{\circ}{M}_w w+\left(\overset{\circ}{M}_q-ma_xU_e-ma_zW_e\right)q \\ +\overset{\circ}{M}_t\delta_t+\overset{\circ}{M}_\delta\delta_e+T_e d_z \\ -\theta\{(mga_z+Bb_z)\cos\theta_e-(mga_x+Bb_x)\sin\theta_e\} \\ -(mga_z+Bb_z)\sin\theta_e-(mga_x+Bb_x)\cos\theta_e \end{matrix}\right\} \tag{4.23}$$

Conditions for Trim

The condition for longitudinal trim may be deduced by noting that in trimmed equilibrium the perturbation variables are all zero and Equations 4.23 reduce to,

$$\begin{aligned} X_e+T_e-(mg-B)\sin\theta_e&=0 \\ Z_e+(mg-B)\cos\theta_e&=0 \\ M_e+T_e d_z-(mga_z+Bb_z)\sin\theta_e-(mga_x+Bb_x)\cos\theta_e&=0 \end{aligned} \tag{4.24}$$

Trim is thus achieved by adjusting thrust T_e, buoyancy force B and centre of volume b_x,b_z simultaneously.

Small Perturbations

The linearised longitudinal equations of motion describing small perturbations about the trim state follow when the trim terms, which sum to zero, are removed from Equations 4.23. Writing the resulting equations in state space form,

$$\mathbf{m}\dot{\mathbf{x}}=\mathbf{a}\mathbf{x}+\mathbf{b}\mathbf{u} \tag{4.25}$$

where,

$$\mathbf{x}^T=\begin{bmatrix}u & w & q & \theta\end{bmatrix}$$

$$\mathbf{u}^T=\begin{bmatrix}\delta_e & \delta_r\end{bmatrix}$$

$$\mathbf{m} = \begin{bmatrix} m_x & 0 & \left(ma_z - \mathring{X}_{\dot{q}}\right) & 0 \\ 0 & m_z & -\left(ma_x + \mathring{Z}_{\dot{q}}\right) & 0 \\ \left(ma_z - \mathring{M}_{\dot{u}}\right) & -\left(ma_x + \mathring{M}_{\dot{w}}\right) & J_y & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{b} = \begin{bmatrix} \mathring{X}_\delta & \mathring{X}_t \\ \mathring{Z}_\delta & 0 \\ \mathring{M}_\delta & \mathring{M}_t \\ 0 & 0 \end{bmatrix}$$

$$\mathbf{a} = \begin{bmatrix} \mathring{X}_u & \mathring{X}_w & \left(\mathring{X}_q - m_z W_e\right) & -\left(mg - B\right)\cos\theta_e \\ \mathring{Z}_u & \mathring{Z}_w & \left(\mathring{Z}_q + m_x U_e\right) & -\left(mg - B\right)\sin\theta_e \\ \mathring{M}_u & \mathring{M}_w & \left(\mathring{M}_q - ma_x U_e - ma_z W_e\right) & -\left\{\left(mga_z + Bb_z\right)\cos\theta_e - \left(mga_x + Bb_x\right)\sin\theta_e\right\} \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

Premultiplying the state equation by the inverse of **m** reduces it to the 'classical' state equation,

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \tag{4.26}$$

where, in this case, it is convenient to write,

$$\mathbf{A} = \mathbf{m}^{-1}\mathbf{a} = \begin{bmatrix} x_u & x_w & x_q & x_\theta \\ z_u & z_w & z_q & z_\theta \\ m_u & m_w & m_q & m_\theta \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

$$\mathbf{B} = \mathbf{m}^{-1}\mathbf{b} = \begin{bmatrix} x_\delta & x_t \\ z_\delta & 0 \\ m_\delta & m_t \\ 0 & 0 \end{bmatrix}$$

Lateral Equations

The linearised lateral equations of motion may be developed similarly,

$$m_y \dot{v} - \left(m a_z + \mathring{Y}_{\dot{p}} \right) \dot{p} + \left(m a_x - \mathring{Y}_{\dot{r}} \right) \dot{r} = \left\{ \begin{aligned} & Y_e + \mathring{Y}_v\, v + \left(\mathring{Y}_p + m_z W_e \right) p + \left(\mathring{Y}_r - m_x U_e \right) r \\ & + \mathring{Y}_\delta\, \delta_r + (mg - B)\phi \cos\theta_e \end{aligned} \right\}$$

$$J_z \dot{r} - J_{xz} \dot{p} + \left(m a_x - \mathring{N}_{\dot{v}} \right) \dot{v} = \left\{ \begin{aligned} & N_e + \mathring{N}_v\, v + \left(\mathring{N}_p + m a_x W_e \right) p + \left(\mathring{N}_r - m a_x U_e \right) r \\ & + \mathring{N}_\delta\, \delta_r + \left(m g a_x + B b_x \right)\phi \cos\theta_e \end{aligned} \right\} \tag{4.27}$$

$$J_x \dot{p} - J_{xz} \dot{r} - \left(m a_z + \mathring{L}_{\dot{v}} \right) \dot{v} = \left\{ \begin{aligned} & L_e + \mathring{L}_v\, v + \left(\mathring{L}_p - m a_z W_e \right) p + \left(\mathring{L}_r + m a_z U_e \right) r \\ & -\left(m g a_z + B b_z \right)\phi \cos\theta_e \end{aligned} \right\}$$

Conditions for Lateral Trim

As before, the condition for lateral trim may be determined by setting all the small perturbation variables to zero. Equations 4. 27 then reduce to,

$$Y_e = L_e = N_e = 0 \tag{4.28}$$

Thus, in trimmed rectilinear flight the residual lateral side-force, yaw and roll moments are all zero.

Small Perturbations

The linearised lateral equations of motion describing small perturbation motion about the trim state may be obtained by removing the zero trim terms from Equations 4. 27. Writing the equations in state space form,

$$\mathbf{m}\dot{\mathbf{x}} = \mathbf{a}\mathbf{x} + \mathbf{b}\mathbf{u} \tag{4.29}$$

where, for lateral motion,

$$\mathbf{x}^T = \begin{bmatrix} v & p & r & \phi \end{bmatrix} \qquad \mathbf{u}^T = \begin{bmatrix} \delta_r \end{bmatrix}$$

$$\mathbf{m} = \begin{bmatrix} m_y & -\left(ma_z + \mathring{Y}_{\dot{p}}\right) & \left(ma_x - \mathring{Y}_{\dot{r}}\right) & 0 \\ -\left(ma_z + \mathring{L}_{\dot{v}}\right) & J_x & -J_{xz} & 0 \\ \left(ma_x - \mathring{N}_{\dot{v}}\right) & -J_{xz} & J_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{b} = \begin{bmatrix} \mathring{Y}_{\delta} \\ 0 \\ \mathring{N}_{\delta} \\ 0 \end{bmatrix}$$

$$\mathbf{a} = \begin{bmatrix} \mathring{Y}_v & \left(\mathring{Y}_p + m_z W_e\right) & \left(\mathring{Y}_r - m_x U_e\right) & (mg - B)\cos\theta_e \\ \mathring{L}_v & \left(\mathring{L}_p - ma_z W_e\right) & \left(\mathring{L}_r + ma_z U_e\right) & -(mga_z + Bb_z)\cos\theta_e \\ \mathring{N}_v & \left(\mathring{N}_p + ma_x W_e\right) & \left(\mathring{N}_r - ma_x U_e\right) & (mga_x + Bb_x)\cos\theta_e \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

Again, premultiplying the state equation by the inverse of **m** reduces it to the 'classical' state equation,

$$\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu} \tag{4.30}$$

where, in the lateral case, it is convenient to write,

$$\mathbf{A} = \mathbf{m}^{-1}\mathbf{a} = \begin{bmatrix} y_v & y_p & y_r & y_\phi \\ l_v & l_p & l_r & l_\phi \\ n_v & n_p & n_r & n_\phi \\ 0 & 0 & 1 & 0 \end{bmatrix} \qquad \mathbf{B} = \mathbf{m}^{-1}\mathbf{b} = \begin{bmatrix} y_\delta \\ 0 \\ n_\delta \\ 0 \end{bmatrix}$$

In deriving the above linearised decoupled longitudinal and lateral small perturbation equations of motion, the following points should be noted:

(i) The derivatives in the **A** and **B** matrices, obtained by dividing the dimensional derivatives by mass and inertia terms are called normalised derivatives and are denoted with a lower case letter. The corresponding equations are referred to as being in normalised form.

(ii) The equations of motion include the additional small perturbation equations,

$$\dot{\theta} = q \qquad \text{and} \qquad \dot{\phi} = p \tag{4.31}$$

since the state matrix **A** must be square to facilitate solution of the equations using matrix methods.

(iii) A further simplification to the equations of motion can be made if level flight is assumed, the airship is trimmed such that $\theta_e = 0$ and neutral buoyancy is assumed such that $mg = B$.

DYNAMIC STABILITY ANALYSIS

A comprehensive investigation of the stability and control characteristics of the airship can only be achieved with a non-linear computer simulation, such as the study carried out by Gomes (1990). However, a useful initial investigation can be achieved by analysis of the small perturbation equations of motion. Since the equations are linear their solution conveniently provides the response transfer functions which are readily analysed with the aid of various computer software tools. It must be recognised, however, that observation of the stability and control characteristics of the airship based on such an analysis must really be limited to small disturbances about a chosen trim condition. In general the fidelity, and hence the value, of the observations deteriorates as the magnitude of the perturbations increases.

The state equation, usually in concise form, is readily solved to obtain the response transfer functions. Since the solution involves algebraic manipulation of matrices it is necessary to first obtain the Laplace transform of the state equation thus, assuming zero initial conditions,

$$s\mathbf{x}(s) = \mathbf{A}\mathbf{x}(s) + \mathbf{B}\mathbf{u}(s) \tag{4.32}$$

It is reasonable to assume zero initial conditions since the motion of interest is defined by small perturbations about a steady datum trim state. The solution of the state equation follows readily,

$$\mathbf{x}(s) = (s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B}\mathbf{u}(s) = \mathbf{G}(s)\mathbf{u}(s) \tag{4.33}$$

where **I** is a unit matrix and **G**(s) is the transfer function matrix, and is typically of the form,

$$\mathbf{G}(s) = \frac{\mathbf{N}(s)}{\Delta(s)} \tag{4.34}$$

where, $\Delta(s) = \det(s\mathbf{I} - \mathbf{A})$ is the characteristic polynomial and common denominator of the transfer functions. Also, $\Delta(s) = 0$ defines the characteristic equation whose zeros, or equivalently eigenvalues of **A**, provide a complete description of stability. The polynomial matrix **N**(s) contains the full set of transfer function numerator polynomials relating each variable in the state vector **x**(s) to each control variable in the input vector **u**(s).

Example (I) The longitudinal state equation for a neutrally buoyant non-rigid airship of mass 86 800 kg flying at a speed of 39 knots at sea level is,

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} -0.0234 & -0.025 & 8.3753 & 0.8264 \\ 6.277E-4 & -0.1485 & 25.014 & -0.0057 \\ 8.287E-5 & 0.0026 & -0.8711 & -0.086 \\ 0 & 0 & 1.0 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} +$$

$$\begin{bmatrix} 0.5008 & 9.64E-3 \\ -0.7604 & 6.75E-6 \\ -0.0521 & 1.015E-4 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_t \end{bmatrix} \tag{4.35}$$

The corresponding matrix of factorised transfer function numerators is,

$$\mathbf{N}(s)=\begin{bmatrix} 0.501(s+0.19)(s^2+2.42E-4s+3.15E-5) & 9.64E-3(s+0.95)(s^2+0.16s+0.0148) \\ -0.76(s+0.0226)(s+0.0335)(s+2.551) & 6.75E-6(s+0.0092)(s+0.024)(s+378.2) \\ -0.052s(s+0.0226)(s+0.1865) & 1.016E-4s(s+0.0327)(s+0.147) \\ -0.052(s+0.0226)(s+0.1865) & 1.016E-4(s+0.0327)(s+0.147) \end{bmatrix} \tag{4.36}$$

and the factorised characteristic polynomial is,

$$\Delta(s)=(s+0.0226)(s+0.8634)(s^2+0.157s+0.0148) \tag{4.37}$$

Thus, the response transfer functions are readily obtained. For example, pitch attitude response to elevator is given by,

$$\frac{\theta(s)}{\delta_e(s)}=\frac{-0.052(s+0.0226)(s+0.1865)}{(s+0.0226)(s+0.8634)(s^2+0.157s+0.0148)}\ \text{rad/rad} \tag{4.38}$$

and, speed response to thrust is given by,

$$\frac{u(s)}{\delta_t(s)}=\frac{9.64E-3(s+0.95)(s^2+0.16s+0.0148)}{(s+0.0226)(s+0.8634)(s^2+0.157s+0.0148)}\ (\text{m/s})/\text{kN} \tag{4.39}$$

Clearly, both of these transfer functions may be simplified by approximate cancellation of some poles and zeros.

Example (ii) For the same airship at the same flight condition the lateral state equation is,

$$\begin{bmatrix} \dot{v} \\ \dot{p} \\ \dot{r} \\ \dot{\phi} \end{bmatrix}=\begin{bmatrix} -0.1355 & -1.4031 & 8.0994 & -2.9513 \\ -0.0035 & -0.2509 & 1.0964 & -0.5277 \\ -0.0046 & -0.0038 & -0.9276 & -0.0070 \\ 0 & 1 & 0 & 0 \end{bmatrix}\begin{bmatrix} v \\ p \\ r \\ \phi \end{bmatrix}+\begin{bmatrix} 0.9283 \\ 0.0092 \\ -0.0609 \\ 0 \end{bmatrix}\delta_r \tag{4.40}$$

The corresponding matrix of factorised transfer function numerators is,

$$\mathbf{N}(s)=\begin{bmatrix} 0.928(s+0.6)(s^2+0.034s+0.67) \\ 0.0092s(s+0.217)(s-6.805) \\ -0.061(s+0.18)(s^2+0.275s+0.524) \\ 0.0092(s+0.217)(s-6.805) \end{bmatrix} \tag{4.41}$$

and the factorised characteristic polynomial is,

$$\Delta(s) = (s+0.128)(s+0.893)(s^2+0.293s+0.543) \tag{4.42}$$

And again, for example, the yaw rate response to rudder transfer function is given by,

$$\frac{r(s)}{\delta_r(s)} = \frac{-0.061(s+0.18)(s^2+0.275s+0.524)}{(s+0.128)(s+0.893)(s^2+0.293s+0.543)} \quad \text{(rad / s) / rad} \tag{4.43}$$

Again, this transfer function may be simplified by approximate cancellation of some poles and zeros.

Example (i) illustrates that, typically, the longitudinal characteristic equation has two real and one complex pair of roots, each root describing a stability mode. Lipscombe (1988) has carried out an analysis of the numerical behaviour of the state matrix using data for a typical modern airship, which provides considerable insight into the stability modes characteristics. The conclusions of this study have subsequently been shown by Gomes (1990) to be in good agreement with observed airship stability characteristics.

For all flight speeds from the hover the longitudinal state matrix in Equation 4.26 can be approximated by,

$$\mathbf{A} = \begin{bmatrix} x_u & 0 & 0 & 0 \\ 0 & z_w & z_q & 0 \\ 0 & m_w & m_q & m_\theta \\ 0 & 0 & 1 & 0 \end{bmatrix} \tag{4.44}$$

without seriously disturbing the zeros of the characteristic equation,

$$\Delta(s) = \det(s\mathbf{I} - \mathbf{A}) = 0 \tag{4.45}$$

Analysis of the eigenvalues of the simplified state matrix **A** enables an approximate description of the stability modes to be made.

The **Surge Mode** is described by a real root of $\Delta(s)$ and is characterised approximately by $(s - x_u)$. The mode appears as an exponential speed subsidence with time constant $T_s = -1/x_u$ and since x_u is a measure of the drag variation due to speed it is usually small and negative and hence the mode is usually stable with a long time constant.

The **Heave Mode** is described at the hover by the second real root of $\Delta(s)$ and is characterised approximately by $(s - z_w)$. However, as the speed increases the mode diverges to a **Pitch Subsidence** which is eventually characterised by $(s - m_q)$ at higher speeds.

At the hover the mode appears as an exponential subsidence in normal velocity with time constant $T_h = -1/z_w$ and since, at this condition, z_w is a measure of drag due to normal velocity it will have a negative value and the mode will be stable. As speed increases z_w will include increasing additional aerodynamic effects resulting from hull lift due to normal velocity, or equivalently hull incidence. Thus at lower speeds the mode will appear more like a stable incidence subsidence with shorter time constant since the value of z_w will increase in a negative sense thereby improving stability. At higher speeds pitch damping effects begin to dominate the mode behaviour and it tends to a stable pitch subsidence with time constant $T_h = -1/m_q$. Generally this mode is described by the larger of the two real roots in $\Delta(s)$.

The **Longitudinal Pendulum Mode** is described by the complex pair of roots of $\Delta(s)$, it is a damped second order oscillation and at the hover it is approximately characterised by $(s^2 - m_q s - m_\theta)$. At the hover the mode is a simple pitch oscillation but as speed increases it diverges to a more complex pitch-incidence oscillation which interacts with the pitch subsidence mode and is characterised by,

$$\left\{ s^2 + \left(\frac{z_q m_w - z_w m_q + m_\theta}{m_q} \right) s + \frac{m_\theta z_w}{m_q} \right\} \tag{4.46}$$

The mode appears as a stable low frequency oscillation in pitch. However, at the hover aerodynamic damping is naturally very low and the mode is approximately neutrally stable, as speed increases the damping ratio increases rapidly to a value in the region of 0.6 at the highest speed.

Example (iii) The validity of the approximate longitudinal model described above is readily demonstrated by applying it to the state matrix of example (i). The approximate stability modes compare with the exact solution as shown in Table 4. 1.

Example (ii) illustrates that, like the longitudinal characteristic equation, the lateral characteristic equation also has two real roots and one complex pair of roots in its solution. As for longitudinal stability, Lipscombe (1988) has analysed the lateral state matrix to identify approximate descriptions of the stability modes and Gomes (1990) has shown the results to be in good agreement with observed airship stability characteristics.

For all flight speeds from the hover, the lateral state matrix (Equation 4.30) can be approximated by,

$$\mathbf{A} = \begin{bmatrix} y_v & 0 & y_r & y_\phi \\ l_v & l_p & l_r & l_\phi \\ n_v & 0 & n_r & n_\phi \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{4.47}$$

without seriously disturbing the zeros of the characteristic equation,

$$\Delta(s) = \det(s\mathbf{I} - \mathbf{A}) = 0 \tag{4.48}$$

Further, at the hover l_p and l_r can also be neglected. Analysis of the eigenvalues of the simplified state matrix **A** enables an approximate description of the stability modes to be made.

Table 4. 1. *Longitudinal Stability Modes*

Neutral Buoyancy - 86 800kg Mass - 39kts Speed - Sea Level				
Longitu'l Stability Mode	*Exact Solution*		*Approximate Solution*	
	Roots	*Characteristic*	*Roots*	*Characteristic*
Surge	$(s + 0.0226)$	Stable T_s= 44.25 sec	$(s + 0.0234)$	Stable T_s= 42.74 sec
Heave	$(s + 0.8634)$	Stable T_h = 1.16 sec	$(s + 0.8625)$	Stable T_h = 1.16 sec
Pendul'm	$\begin{pmatrix} s^2 + 0.157s \\ +0.0148 \end{pmatrix}$	Stable $\omega_p = 0.12 rad/s$ $\zeta_p = 0.65$	$\begin{pmatrix} s^2 + 0.157s \\ +0.0148 \end{pmatrix}$	Stable $\omega_p = 0.12 rad/s$ $\zeta_p = 0.65$

The **Yaw Subsidence Mode** is described by a real root of $\Delta(s)$ and at the hover it is approximately characterised by,

$$\left(s - \left\{n_r + \left(\frac{n_\phi l_v - n_v l_\phi}{y_v l_\phi - y_\phi l_v}\right) y_r\right\}\right) \tag{4.49}$$

as speed increases the mode characteristic diverges to $(s - y_v - n_r)$. The approximate time constant of the exponential subsidence, which is usually stable, is given by,

(i) at the hover

$$T_y = \frac{-1}{\left\{ n_r + \left(\dfrac{n_\phi l_v - n_v l_\phi}{y_v l_\phi - y_\phi l_v} \right) y_r \right\}} \tag{4.50}$$

(ii) at speed

$$T_y = \frac{-1}{(y_v + n_r)} \tag{4.51}$$

At the hover T_y is very large indeed indicating neutral stability for all practical purposes, but T_y rapidly reduces with speed to a value in the order of one second at higher speeds. Since the mode characteristic is significantly dependent on the yaw damping derivative n_r the observation is entirely consistent with the increase in yaw damping due to speed.

The **Sideslip Subsidence Mode** is described by the second real root of $\Delta(s)$ and at the hover it is approximately characterised by,

$$\left(s - y_v - \frac{y_\phi l_v}{l_\phi} \right) \tag{4.52}$$

and as speed increases the mode characteristic diverges such that y_v tends to y'_v and y_ϕ tends to y'_ϕ where,

$$y'_v = y_v - \left(\frac{y_r n_v}{n_r} \right) \quad \text{and} \quad y'_\phi = y_\phi - \left(\frac{y_r n_\phi}{n_r} \right) \tag{4.53}$$

The mode appears as a stable exponential subsidence in lateral velocity with approximate time constant,

(i) at the hover

$$T_v = -\left(\frac{l_\phi}{y_v l_\phi + y_\phi l_v} \right) \tag{4.54}$$

(ii) at speed

$$T_v = -\left(\frac{l_\phi n_r}{n_r(y_v l_\phi + y_\phi l_v) - y_r(n_v l_\phi + n_\phi l_v)}\right) \tag{4.55}$$

Again, at the hover T_v is very large and the mode is approximately neutrally stable. As speed increases T_v rapidly reduces to a value in the order of five seconds, therefore the sideslip subsidence is characterised by the smaller of the two real roots of $\Delta(s)$.

The **Oscillatory Roll Mode** is described by the complex pair of roots of $\Delta(s)$ and at the hover it is approximately characterised by,

$$\left\{s^2 - \left(\frac{y_\phi l_v}{l_\phi}\right)s - l_\phi\right\}$$

and at speed by,

$$\left\{s^2 - \left(l_p + \frac{y'_\phi l_v}{l_\phi}\right)s - l_\phi\right\} \tag{4.56}$$

where y'_ϕ is defined under *Sideslip Subsidence Mode* above. Typically the mode appears as a pendulum oscillation in roll which is caused by the metacentric height, defined by l_ϕ, which is always negative. Since the natural aerodynamic roll damping l_p is usually very small most of the useful damping is provided by the rolling moment due to sideslip l_v in combination with y_ϕ the side-force due to roll angle. For stability,

$$\left(\frac{y_\phi l_v}{l_\phi}\right) < 0 \qquad \text{or} \qquad \left(l_p + \frac{y'_\phi l_v}{l_\phi}\right) < 0 \tag{4.57}$$

and this depends to a large extent on the magnitude and sign of y_ϕ. This approximate analysis indicates that y_ϕ will be stabilising when the airship is buoyant and vice versa. However, Gomes (1990) has shown that, typically, this mode remains stable over the working range of buoyancy from positive, through neutral to negative.

Example (iv) The validity of the approximate lateral model described above is also readily demonstrated by applying it to the state matrix of example (ii). The approximate stability modes compare with the exact solution as shown in Table 4. 2.

Table 4. 2: *Lateral Stability Modes*

Neutral Buoyancy - 86 800kg Mass - 39kts Speed - Sea Level				
Lateral Stability Mode	*Exact Solution*		*Approximate Solution*	
	Roots	*Characteristic*	*Roots*	*Characteristic*
Yaw Subsidence	$(s+0.893)$	Stable $T_y = 1.12$ sec	$(s+0.904)$	Stable $T_y = 1.11$ sec
Sideslip Subsidence	$(s+0.1280)$	Stable $T_v = 7.80$ sec	$(s+0.1252)$	Stable $T_v = 7.99$ sec
Roll Oscillation	$\begin{pmatrix} s^2 + 0.293s \\ +0.543 \end{pmatrix}$	Stable $\omega_r = 0.74$ $rad\ /\ s$ $\zeta_r = 0.20$	$\begin{pmatrix} s^2 + 0.285s \\ +0.551 \end{pmatrix}$	Stable $\omega_r = 0.74$ $rad\ /\ s$ $\zeta_r = 0.19$

Clearly, for both longitudinal and lateral dynamics, the approximate and exact stability modes compare very well. However, the approximate model is not particularly useful for producing a numerical solution, although this may be helpful for confirming the output of a computer program. The real value of the approximate model is to identify those aerodynamic stability derivatives which are dominant in the determination of the response dynamics of the airship. Further analysis of the relevant derivatives then enables the aerodynamic, mass and inertia properties associated with particular mode characteristics to be identified.

CONTROL AND RESPONSE

In order to illustrate the control and response characteristics of the airship it is convenient to use the previously described examples. Although the examples refer to a very large non-rigid airship the response characteristics are quite typical of the modern airship. However, a smaller airship would generally be expected to respond to controls a little more quickly.

The **longitudinal response to elevator** is shown on Figure 4.5 for which the input command is a 0.2 rad (11.5 deg) elevator step such as to cause a nose down response. In aerodynamic terms the input is relatively large since a deflection angle in the range 0.26 to 0.35 rad would cause a flap type control surface to stall with the consequent loss of effectiveness. The magnitudes of the response variables are very small and the time taken for the transient to settle is in the order of one minute. This clearly demonstrates a relatively low longitudinal control power and a rather sluggish response characteristic. The airship, however, is quite stable - as predicted in example (iii) - and the stability modes, which determine the transient characteristics, are quite distinct in the response as indicated on Figure 4.5.

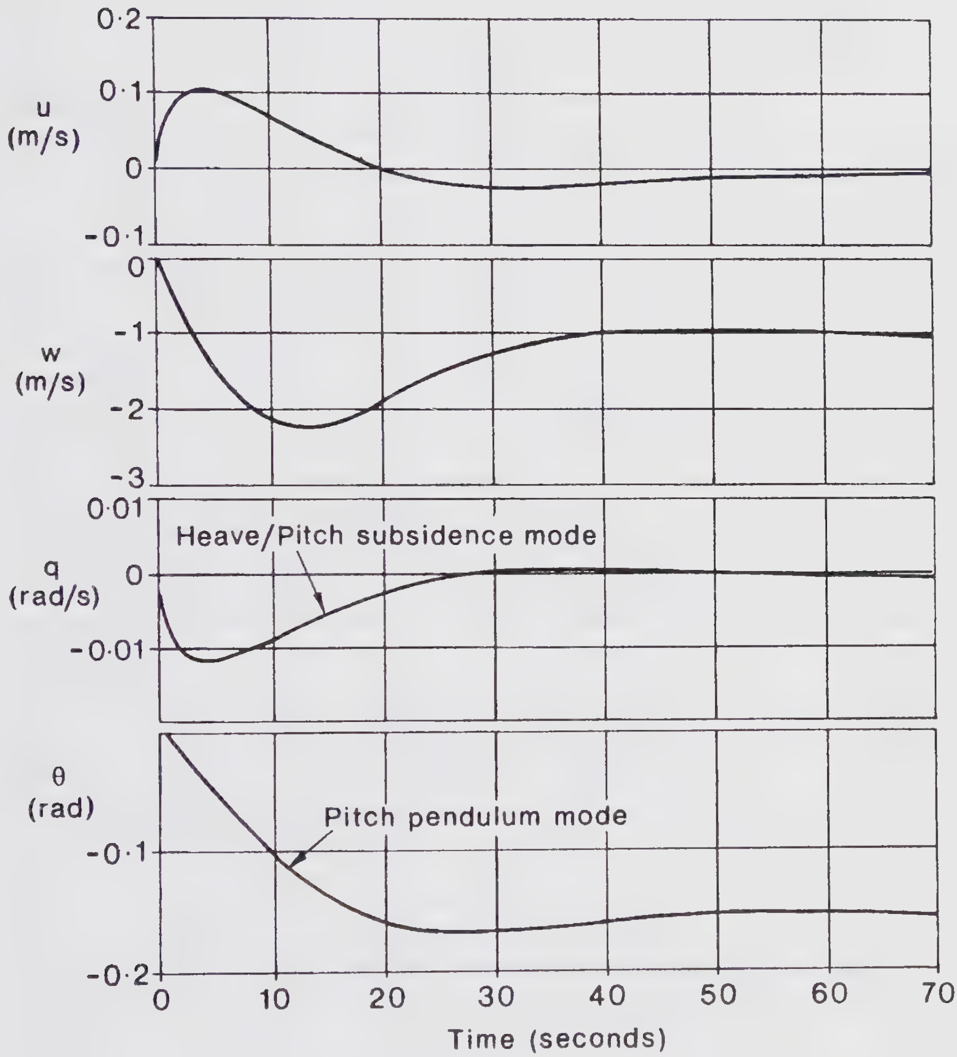

Figure 4.5. Longitudinal response to a 0.2rad elevator step input.

Since the response to elevator is predominantly pitch it is instructive to analyse the appropriate transfer function which is given in example (i),

$$\frac{\theta(s)}{\delta_e(s)} = \frac{-0.052(s+0.0226)(s+0.1865)}{(s+0.0226)(s+0.8634)(s^2+0.157s+0.0148)} \text{ rad / rad} \tag{4.58}$$

The surge mode pole (s + 0.0226) is cancelled by a numerator zero in the $\theta(s)$, $q(s)$ and $w(s)$ response transfer functions implying that the mode is decoupled from pitch-incidence motion and therefore does not appear in the responses. The $u(s)$ response transfer function numerator includes a numerically small complex pair of zeros that may be approximated by s^2. Although the surge mode describes a velocity response characteristic it is very nearly cancelled by one of these zeros. This implies that the surge mode is not significantly excited by elevator inputs. This is not surprising since elevator deflection produces pitching moment response accompanied by a very small increase in drag and it is the small drag force change which excites the mode.

The heave/pitch subsidence mode, described by the pole $(s + 0.8634)$, appears to the pilot as a short time constant lag in pitch response. This is most clearly visible as the initial exponential rise in pitch rate q response shown on Figure 4.5.

The longitudinal pendulum mode is described by the complex pair of poles $(s^2 + 0.157s + 0.0148)$ and appears to the pilot in all response variables as a well damped second order like oscillation although it is most distinct in the pitch attitude θ response as might be expected.

The **longitudinal response to** a 5kN step increase in **thrust** is shown on Figure 4.6. It is clear that, although the engines are mounted well below the centre of gravity the pitch response to a thrust change is very small. The only significant response is in velocity u as might be expected. Again, the general magnitude and time scale of response confirms that longitudinal control power is low and response is sluggish.

The speed response to thrust transfer function given in example (i) is,

$$\frac{u(s)}{\delta_t(s)} = \frac{9.64E-3(s+0.95)(s^2+0.16s+0.0148)}{(s+0.0226)(s+0.8634)(s^2+0.157s+0.0148)} \text{ (m / s) / kN} \tag{4.59}$$

or, very approximately,

$$\frac{u(s)}{\delta_t(s)} = \frac{0.01}{(s+0.0226)} \text{ (m / s) / kN} \tag{4.60}$$

Thus speed change is the dominant response to thrust and is almost entirely determined by the surge mode lag, the corresponding exponential response is very clearly seen in Figure 4.6.

An analysis of the remaining longitudinal thrust response transfer functions given in example (i) shows that, in every case the surge mode pole is approximately cancelled by a numerator zero. This simply confirms the earlier observation that the surge mode is largely decoupled from pitch-incidence motion. The remaining longitudinal modes are quite visible in the θ, q and w responses shown on Figure 4.6. However, their transient magnitudes are very small indicating a significant insensitivity to thrust change.

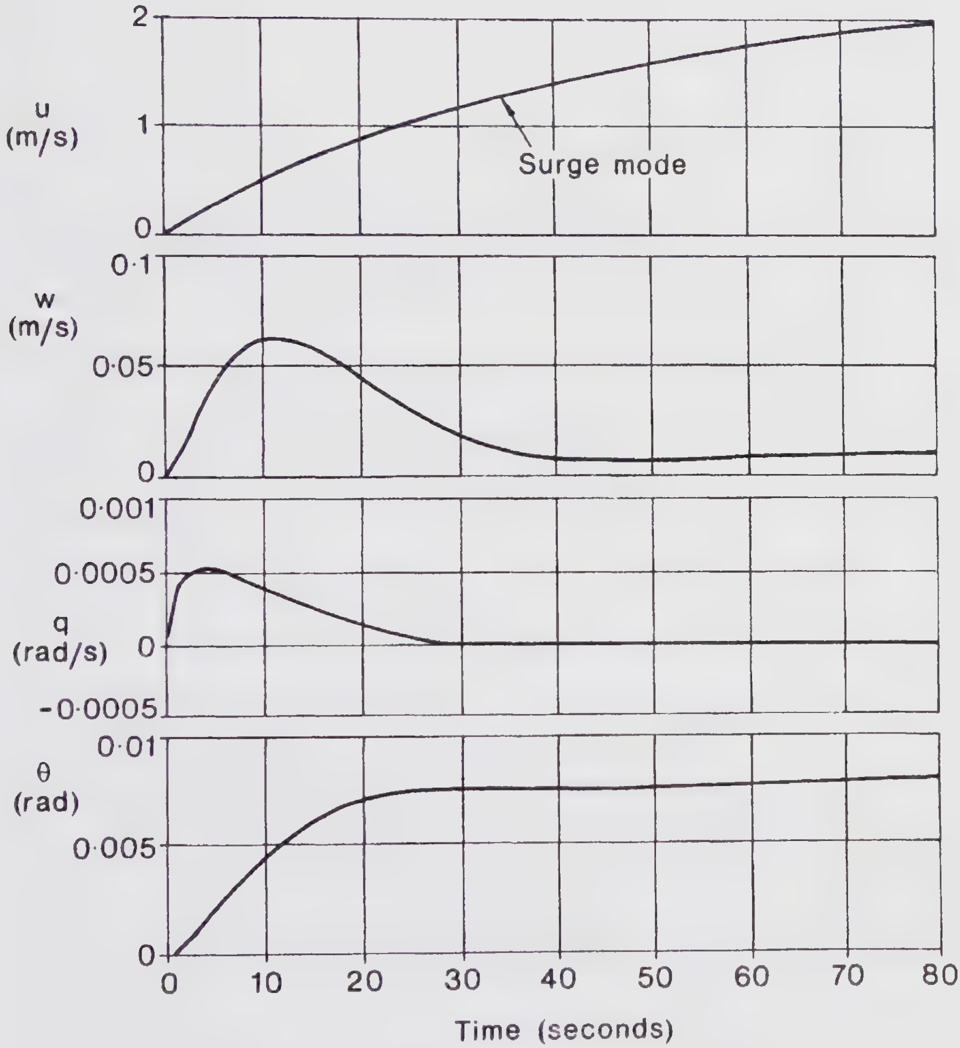

Figure 4.6. Longitudinal response to a 5kN step increase in thrust.

The **lateral response to** a 0.2 rad **step command input to rudder** is shown on Figure 4.7. Again, in aerodynamic terms this is a relatively large input and as the response magnitudes are very small it is clear that rudder control power is low. The transients, however, settle in approximately 30 seconds, indicating that lateral response is a little less sluggish than longitudinal response. The lateral stability modes are quite visible in the responses as indicated on Figure 4.7 although some mode coupling is evident. Lateral mode coupling to varying degrees is quite typical in most air vehicles.

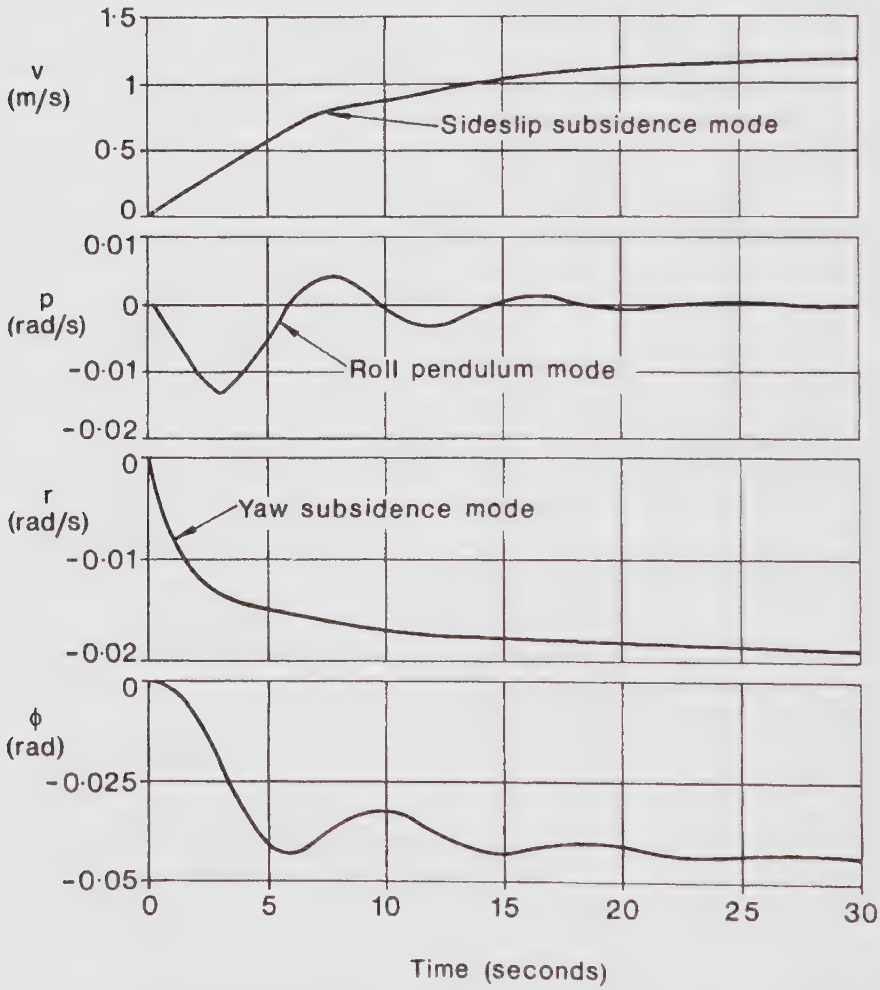

Figure 4.7. Lateral response to a 0.2rad rudder step input.

The sideslip response to rudder transfer function is given in example (ii) as,

$$\frac{v(s)}{\delta_r(s)}=\frac{0.928(s+0.6)\left(s^2+0.034s+0.67\right)}{(s+0.128)(s+0.893)\left(s^2+0.293s+0.543\right)}\ \text{(m / s) / rad}$$
(4.61)

or, very approximately,

$$\frac{v(s)}{\delta_r(s)}=\frac{0.928}{(s+0.128)}\ \text{(m / s) / rad} \tag{4.62}$$

Thus sideslip response to rudder is dominated by the sideslip subsidence mode and the corresponding exponential characteristic is very obvious as indicated on Figure 4.7.

Similarly, the yaw rate response to rudder transfer function given in example (ii) is,

$$\frac{r(s)}{\delta_r(s)}=\frac{-0.061(s+0.18)\left(s^2+0.275s+0.524\right)}{(s+0.128)(s+0.893)\left(s^2+0.293s+0.543\right)}\ \text{(rad / s) / rad} \tag{4.63}$$

or, very approximately,

$$\frac{r(s)}{\delta_r(s)}=\frac{-0.061}{(s+0.893)}\ \text{(rad / s) / rad} \tag{4.64}$$

In this instance yaw rate response is dominated by the yaw subsidence mode and the lag characteristic is clearly visible on Figure 4.7.

The roll oscillation mode, described by the complex pair of poles (s^2 + 0.293s + 0.543), is clearly visible in both roll rate and roll attitude response as might be expected. Analysis of the appropriate transfer functions in example (ii) indicates that the sideslip subsidence mode cancels approximately implying that its contribution to roll response is negligible. This is not the case with the yaw subsidence mode and the lag characteristic couples with the roll responses a little but is not particularly evident in Figure 4.7.

Control and response at the hover differs to that in normal flight since, in general, control is only required to maintain the hover in the presence of atmospheric disturbances or, to initiate transition to normal flight. Clearly, at the hover no aerodynamic control is available and the aerodynamic contribution to transient response dynamics is negligibly small. Effective control at the hover can therefore only be achieved by thrust vectoring and by differential thrust control. However, to put this into context, it was reported that in recent flight trials appreciable aerodynamic control was available at speeds as low as two to three knots. Analysis of control and response at the hover requires a more detailed linearised model than that described above. In particular, the thrust model developed in Equations 4.19-4.22 must be included in the linear model to retain the thrust control variables explicitly.

Dynamic response at the hover is characterised by the stability modes which in turn are determined by the aerodynamic properties. Since the aerodynamic contribution is negligibly small both the longitudinal and lateral stability modes are only marginally stable. Consequently, both the longitudinal and lateral non-oscillatory stability modes have time constants measured in hours rather than seconds! Similarly, the oscillatory stability modes have negligible aerodynamic damping. For the airship example referred to above, at the hover the longitudinal pendulum mode has a frequency of 0.29 rad/s and near zero damping ratio, and the roll oscillation has a frequency of 0.73 rad/s and near zero damping ratio. Comparing these frequencies with those given in examples (iii) and (iv) clearly indicates that virtual inertia effects have a significant influence on longitudinal dynamics and an insignificant influence on lateral dynamics.

It may be concluded that, for all practical purposes the airship appears to the pilot to be neutrally stable at the hover. The only significantly visible response dynamics being the undamped oscillatory modes. For analysis, the approximate models described by Equations 4.44 to 4.57 provide an adequate description of stability characteristics at the hover.

The effects of **non-neutral buoyancy** have been investigated by Gomes (1990) for a typical range of variation in airship mass about the neutrally buoyant condition. In general the resultant variations in control, stability and response were found to be negligible. At non-neutral buoyancy, however, it becomes necessary to trim the airship to generate aerodynamic lift to balance the difference between the weight and buoyancy force. This in turn creates additional drag with the consequent penalty in performance.

AUTOMATIC FLIGHT CONTROL

As far as is known automatic flight control systems have not found extensive application to the airship, including modern technology non-rigid airships developed in the last 20 years or so. An exception to this is the Sentinel 1000 prototype airship - a technology demonstrator for an early warning radar platform for maritime operations in the USA. This airship was designed from the outset to capitalise on the benefits derived from the use of an advanced technology flight control system concept. Early reports suggest that the stability and control characteristics of the Sentinel 1000 are superior to those of the most previous airship designs, which do not include any form of automatic flight control.

It is important to recognise that a flight control system can only modify the flying qualities of the airship within limits imposed by its physical properties, the number and type of controls and their control power. In particular, aerodynamic controls are not very effective, especially at low speeds, and this will limit the scope for automatic control. Low control power means high control system gains for a given system performance. This in turn can lead to difficulties with control system authority in manoeuvring flight and safety in the event of system malfunction. Furthermore, full automatic control at speeds down to and including the hover will require automatic control of thrust and thrust vectoring in addition to the usual aerodynamic surfaces.

Replacement of the primary mechanical flying controls with an electrically or optically signalled FBW system offers considerable scope for improvements in basic flying and handling qualities. Significant lost motion in mechanical systems has seriously reduced the limited control power of earlier airships with the consequent degradation in handling quality. By way of contrast, the Sentinel 1000 was fitted with an optically signalled primary flying control system; and pilots report that dramatically superior handling quality and response to pilot input at all speeds has been very apparent. The message to future designers of airships is, therefore, clear.

A FBW system installation introduces many new considerations to the overall design process. Since the primary flying control system comprises novel control inceptors, a digital control computer, hydraulic or electric control surface actuators and an artificial feel system the implications for safety become critically important. Such systems, however, have already been successfully developed for aircraft, the technology is available and can be exploited for the airship at relatively low development cost.

When an airship is fitted with a FBW system it is a relatively simple matter to extend the system function to include control and stability augmentation. The addition of motion sensors, for example roll, pitch and yaw rate gyro's, enables feedback control loops to be closed. The feedback gain functions are readily designed to augment the stability and response characteristics as desired. Note that full three axis stability augmentation would require control of equivalent aileron as well as equivalent elevator and rudder. Further, in addition to stability augmentation, control response can be independently augmented in order to tailor handling qualities directly. This may be achieved by the introduction of shaping filters to the command signals derived from the pilots controls. The application of these simple but powerful augmentation techniques has significant implications for future airship development. Full augmentation can ensure excellent handling qualities with a reduced pilot workload and can lead to an extended operational flight envelope to include roles and conditions hitherto considered impractical.

The automatic flight control system can also incorporate autopilot functions to further enhance the operational capability of the airship. Simple autopilot modes like speed hold relieve the pilot of monotonous flying tasks whereas complex modes such as automatic flight path control can fly the airship with precision in circumstances when it may not be practical or appropriate for the pilot to do so. Most autopilot functions would require the addition of appropriate sensors and some expansion of the capability of the flight control computer. However, as for the previously described flight control systems, the technology exists and may readily be applied to the airship. The most likely foreseeable difficulty would seem to be the limited aerodynamic control power as this could restrict autopilot performance. It is therefore likely that automatic thrust control would be an essential feature of all but the simplest autopilot modes.

FLYING AND HANDLING QUALITIES

Flying qualities requirements for the airship have not previously been developed to the standards enjoyed by other modern air vehicles. Traditionally, flying qualities appear to have been determined entirely by the basic aerodynamic stability and control properties of the airship, and since it is reasonably stable, and hence safe, this has been regarded as acceptable. There is now no doubt that the application of advanced technology flight control to the airship can bring substantial benefits. The subject, however, is still in its infancy and there is some scope, and an outstanding need, for improvement in the understanding of airship flying qualities. In particular there is a need to identify and quantify the parameters that determine what are considered to be excellent flying qualities.

Since flight control systems introduce additional dynamics to the overall airship behaviour it becomes characterised by what, today, is called a high order system. With such systems it is no longer appropriate to expect excellent flying qualities simply by augmenting stability and control to meet classical criteria. The designers of advanced technology flight control systems for conventional aircraft have addressed this problem and new solutions and criteria are beginning to emerge. Gomes (1990) has reviewed the applicability of a more relevant criterion to the airship. He concluded that the principles are very relevant but the quantifiable criteria are not. There is, therefore, an exciting research challenge awaiting attention if the best is to made of the future advanced technology airship.

ACKNOWLEDGEMENTS

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SYMBOLS

$\mathbf{A}$ state matrix
$\mathbf{B}$ input matrix
B buoyancy force
$\mathbf{G}$ transfer function matrix
$\mathbf{I}$ identity matrix
I moment of inertia
J apparent moment of inertia
L rolling moment
M pitching moment
$\mathbf{N}$ matrix of numerator polynomials
$\mathbf{a}$ state matrix
a cg co-ordinate
$\mathbf{b}$ input matrix
b cb co-ordinate
d thrust co-ordinate
g gravitational constant
l normalised rolling moment
$\mathbf{m}$ mass matrix
m normalised pitching moment
m mass
n normalised yawing moment
o origin of body axes
Δ characteristic polynomial
δ control angle
ζ damping ratio
θ pitch attitude
N yawing moment
T thrust
T time constant
U axial velocity
V lateral velocity
V total velocity
W normal velocity
X axial force
Y lateral force
Z normal force
p roll rate perturbation
q pitch rate perturbation
r yaw rate perturbation
s Laplace operator
$\mathbf{u}$ input vector
u axialvelocity perturbation
v lateral velocity perturbation
w normal velocity perturbation
$\mathbf{x}$ state vector
x normalised axial force
y normalised lateral force
z normalised normal force
μ thrust elevation angle
ϕ roll attitude
ψ yaw attitude
ω frequency

SUBSCRIPTS

a	aerodynamic	r	equivalent rudder
b	buoyancy	r	yaw rate
c	control	r	roll pendulum mode
e	trim equilibrium	s	starboard
e	equivalent elevator	s	surge mode
g	gravitational	t	thrust
h	heave mode	u	axial velocity
o	total	v	lateral velocity
p	roll rate	v	sideslip mode
p	pitch pendulum mode	w	normal velocity
p	port	x	body axis reference
p	propulsion	y	body axis reference
q	pitch rate	y	yaw subsidence mode
δ	control angle	z	body axis reference
θ	pitch attitude	ϕ	roll attitude

STABILITY AND CONTROL DERIVATIVES

Dimensional derivatives denoted thus $\mathring{M}_q = \dfrac{\partial M}{\partial q}$ etc.

Normalised derivatives denoted thus $y_v = \dfrac{\partial y}{\partial v}$ etc.

5

Propulsion

I. Cheeseman

INTRODUCTION

All propulsion systems must include three components. These are a source of energy (the fuel), a prime mover (the engine) and the propulsor which produces the force to propel the vehicle. Each of these components will be considered in turn. The choices which the designer has to make in selecting a system for a vehicle depends on the performance required for the roles envisaged for it. It must not be forgotten that engines perform duties other than just providing power to propel the vehicle. They also power auxiliary systems for example to provide electrical and/or hydraulic power for use by installed equipment or in the control of the vehicle. The effect of these auxiliary roles on the choice of the propulsive system will be briefly examined.

THE PROPULSOR

The efficient use of friction drive through a wheel is not available to airborne craft. The mechanism used within the atmosphere involves ejecting material to produce a rate of change of momentum in the direction opposite to the required force. In the case of the rocket this is chemically produced gas but air is accelerated for most airborne vehicles. For the airship this still leaves a variety of propulsive systems and to make a selection it is necessary to establish the basic parameters which determine the characteristic performance.

The most basic, but probably the most illuminating, is the actuator disc model. This assumes a loss-less system which can be neither bettered nor unfortunately achieved. Having developed this model it will then be extended by including factors which degrade the performance.

Actuator Disc Theory

It is assumed that the propulsor may be represented by an infinitely thin disc of area A which supports a pressure discontinuity, the static pressure on the upper surface, p, is increased on the lower surface to p+Δp. The Propulsive force, T, is then:

$$T = (p+\Delta p - p)A = \Delta p.A \quad (5.1)$$

This thin disc is the actuator disc and is shown in Figure 5.1. In inviscid flow consider a cylindrical control surface which has a radius R_1 far upstream, (plane A), encloses the propulsor of area $A = \pi R^2$ (between planes B & C) and its slip-stream which achieves equilibrium flow conditions at plane D. The flow which passes through the propulsor will be enclosed by streamlines up and downstream, the latter being the wake boundary. In co-ordinates fixed in the propulsor, which is moving forward with velocity V, the air at plane A is moving towards the propulsor with velocity V and is at ambient static pressure p_∞. At plane B, which is immediately upstream of the actuator disc, the static pressure has risen to p and the velocity to V + v_i. Immediately downstream of the disc at plane C the static pressure has increased to $p+\Delta p$ but because the velocity is continuous it has the same value as at plane B. At plane D the velocity is $V + v_2$ and the static pressure p_2, the latter being for the more general formulation of the problem. At plane D and outside of the slip-stream, the flow velocity is V and the static pressure p_∞ as no energy has been added to this air by the propulsor. The air within the stream tube is the same at all planes so conservation of volume flow, Q, dictates that:

$$Q = \pi R_1^2 V = \pi R^2 (V + v_i) = \pi R_2^2 (V + v_2) \quad (5.2)$$

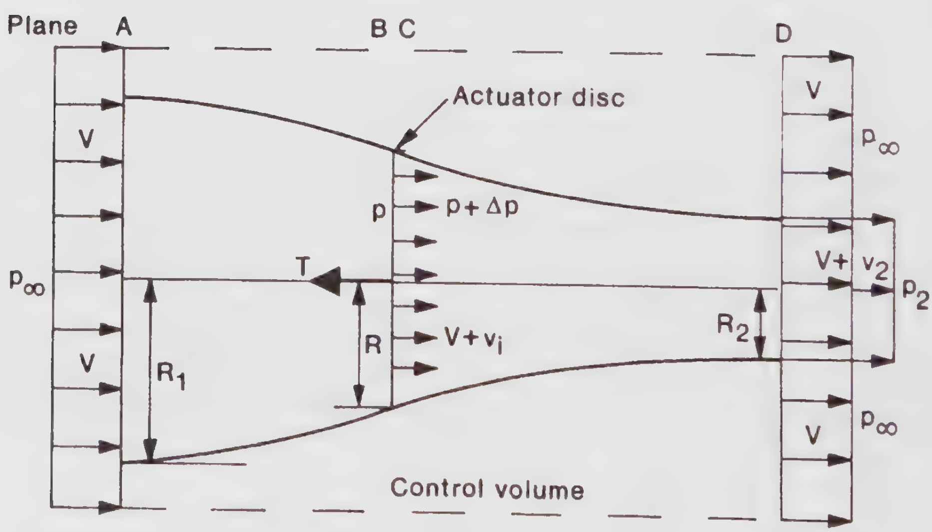


Figure 5.1. Actuator disc in axial motion.

Considering the control volume it is clear that as the area outside the stream-tube at plane D is greater than at plane A, air must have entered the volume through its curved sides. This inflow Q_i is given by:

$$Q_i = \pi(R_1^2 - R_2^2)V + \pi R_2^2(V + v_2) - \pi R_1^2 V = \pi R_2^2 v_2 \tag{5.3}$$

and it has velocity V in the axial direction. The total forces and rate of change of momentum on the surfaces of the control volume are next considered.

The momentum entering the control volume per unit time through plane A and the curved sides is:

$$M_{in} = \rho\pi(R_1^2 V + R_2^2 v_2)V$$

and leaving through plane D is:

$$M_{out} = \rho\pi(R_1^2 - R_2^2)V^2 + \rho\pi R_2^2(V + v_2)^2$$

The rate of change of momentum in the axial direction is:

$$M_{out} - M_{in} = \rho\pi R_2^2(V + v_2)v_2 \tag{5.4}$$

This equals the total force acting in the axial direction which is the thrust T and the difference of the static pressure on planes A and D. Thus:

$$T + \pi R_1^2 p_\infty - \pi(R_1^2 - R_2^2)p_\infty - \pi R_2^2 p_2 = \rho\pi R_2^2(V + v_2)v_2$$

which simplifies to:

$$T = \rho\pi R_2^2(V + v_2)v_2 + \pi R_2^2(p_2 - p_i) \tag{5.5}$$

Using Equations 5.1 & 5.2, Equation 5.5 may be written as:

$$T/A = \Delta p = \rho(V + v_i)v_2 + (p_2 - p_\infty)(V + v_i)/(V + v_2) \tag{5.6}$$

Bernoulli's equation may be applied between planes A & B and between C & D as no work is done on the fluid in those regions and the total head remains constant.

For planes A to B:

$$p_\infty + ½\rho V^2 = p + ½\rho(V + v_i)^2$$

and for planes C to D:

$$p_2 + ½\rho(V + v2)^2 = p + \Delta p + ½\rho(V + v_i)^2$$

By subtraction:

$$\Delta p = p_2 - p_\infty + \rho (V + \tfrac{1}{2}v_i)v_2 \qquad (5.7)$$

From Equations 5.6 & 5.7:

$$\rho (v_2 + \tfrac{1}{2}v_i)v_2 = (p_2 - p_\infty)(V + v_i)/(V + v_2) \qquad (5.8)$$

The classical actuator disc assumption is that $p_2 = p_\infty$ in which case:

$$v_2 = 2v_i \qquad (5.9)$$

Substituting in Equation 5.6:

$$T/A = 2\rho (V + v_i)v_i \qquad (5.10)$$

T/A is the thrust per unit area of the propulsor and is called the propeller or disc loading.

The power P which must be supplied to the propulsor is equal to the rate at which kinetic energy is given to the fluid. For the control surface of Figure 5.1, the kinetic energy added to the fluid is the difference between the rate at which it leaves:

$$K_{out} = \tfrac{1}{2}\rho\pi \{(R_1^2 - R_2^2)V^3 + R_2^2(V + v_2)^3\}$$

and enters:

$$K_{in} = \tfrac{1}{2}\rho\pi (R_1^2 V + R_2^2 v_2)V^2$$

So $P = K_{out} - K_{in}$ which may be expressed, using Equations 5.3 & 5.6, as:

$$P/A = T/A\,(V + \tfrac{1}{2}v_2) + \tfrac{1}{2}(p_2 - p_\infty)(v_2/(V + v_2)) \qquad (5.11)$$

In the classical case $p_2 = p_\infty$ so $v_2 = 2v_i$ and:

$$P/A = T/A\,(V + v_i) \qquad (5.12)$$

The term TV is the useful work done per unit time by the force T while Tv_i is the non-useful energy in the slip-stream. The Froude efficiency ζ, which is the ratio of the useful work done to the total energy added per unit time, is given by:

$$\zeta = TV/T(V + v_i) \qquad (5.13)$$

From Equation 5.10 v_i may be found and substituted into Equation 5.13 giving:

$$\zeta = 2/(1 + (1 + 2T/\rho AV^2)^{0.5}) \qquad (5.14)$$

For a given flight condition ρ and V are determined so the only variable is the propeller loading T/A. Figure 5.2 shows the propulsive efficiency ζ plotted against $T/\rho AV^2$. This Figure shows that for fixed pressure altitude ρ and speed V the efficiency decreases as propulsor loading increases. For a constant propulsor loading and pressure altitude the efficiency increases as forward speed increases. This is because the slip-stream velocity becomes more nearly equal to the forward speed. A typical aircraft propeller operating at near peak efficiency has a value of $T/\rho AV^2$ in the range 1.5 to 5. For a large turbo-fan engine to approach the same efficiency it will have to operate at high altitude and high Mach number. It is clear from this simple analysis that the only efficient propulsor for a slow vehicle which operates at low altitude, like the airship, is one which has a low disc loading and that means a propeller.

Airship propulsion systems may be required to produce thrust efficiently in the hover. The static efficiency of a propulsor cannot be assessed from Equation 5.14 since it does no useful work. However, putting V = 0 into Equations 5.10 & 5.14 then:

$$P/T = (T/A\rho)^{0.5} \tag{5.15}$$

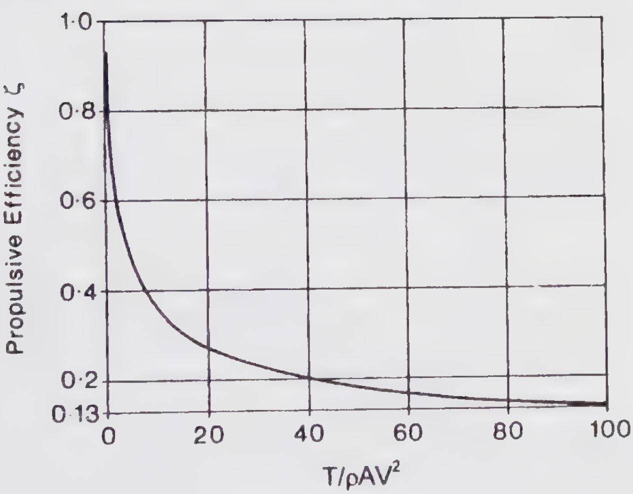


Figure 5.2. Propulsive efficiency vs. $T/\rho AV^2$.

The power needed to produce unit thrust, P/T, is plotted in Figure 5.3 as a function of propulsor loading for standard day conditions. Typical propulsor loadings are also shown.

Actuator disc theory provides the ideal, but not physically realisable, performance. Blade element theory introduces the properties of the lifting surfaces which produce the thrust.

Typical Values of T/A	
Propulsor	T/A (kN/m^2)
Helicopter rotor	0.2 – 0.5
Propeller	2 – 6
Fan jet	25 – 50
Pure jet	200 - 300

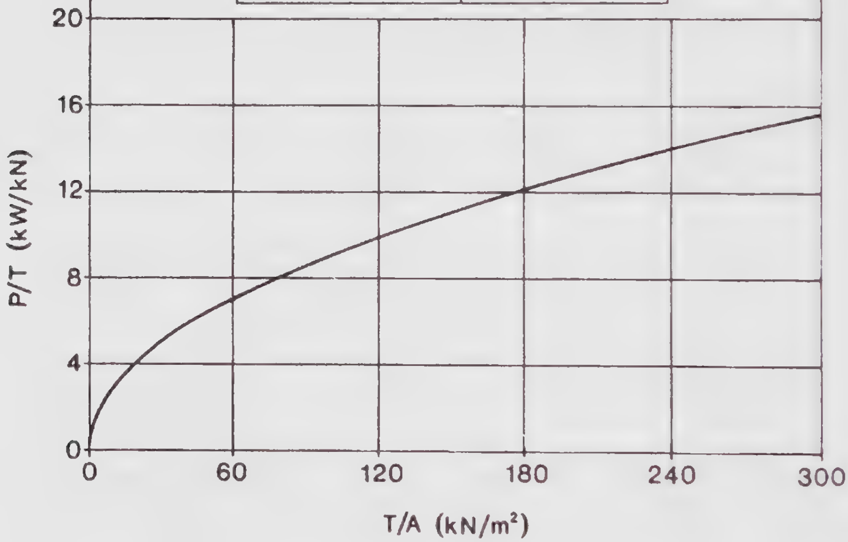


Figure 5.3. Power per unit static thrust vs. propulsor loading.

Blade Element Theory

Propeller blades may be considered as twisted wings. If the radius of the propeller is R, a cross-section of the blade at a distance r from the centre of rotation is shown in Figure 5.4. The velocities incident on the blade section are Ωr, owing to rotation at angular velocity Ω, V the forward and v_i the induced velocity. The aerofoil produces lift and drag forces per unit span of dL and dD normal to and along the resultant velocity W. These are resolved to give components dT normal to and dH in the plane of rotation. The blade section has an angle of attack of θ and the inflow angle is ϕ. If a_1 is the lift curve slope $dC_L/d\alpha$ and C_D the drag coefficient of the blade section for the local Mach number W/a, a being the speed of sound, then for a spanwise width of dr:

$$dL = \tfrac{1}{2}\rho c\Omega^2 R^3\{ (x + (v_i \sin\phi)/\Omega R)^2 + (J + \lambda)^2\} a_1(\theta - \phi)dx \tag{5.16}$$

and,

$$dD = \tfrac{1}{2}\rho c\Omega^2 R^3\{(x + (vi \sin\phi)/\Omega R)^2 + (J + \lambda)^2\} Cddx \tag{5.17}$$

where c = the local chord, $J = V/\Omega R$, $x = r/R$, $dx = dr/R$ and $\lambda = v_i \cos\phi/\Omega R$. a_1 is not a constant but a function of incidence which must extend into the region of stall.

Resolving these forces normal to and along the plane of rotation gives:

$$dT = dL\cos\phi - dD\sin\phi \tag{5.18}$$

and,

$$dH = dL\sin\phi + dD\cos\phi \tag{5.19}$$

where:

$$\phi = \tan^{-1}\{(V + v_i \cos\phi)/(\Omega Rx + v_i \sin\phi)\} = \tan^{-1}\{(J + \lambda)/(x + \lambda\tan\phi)\} \tag{5.20}$$

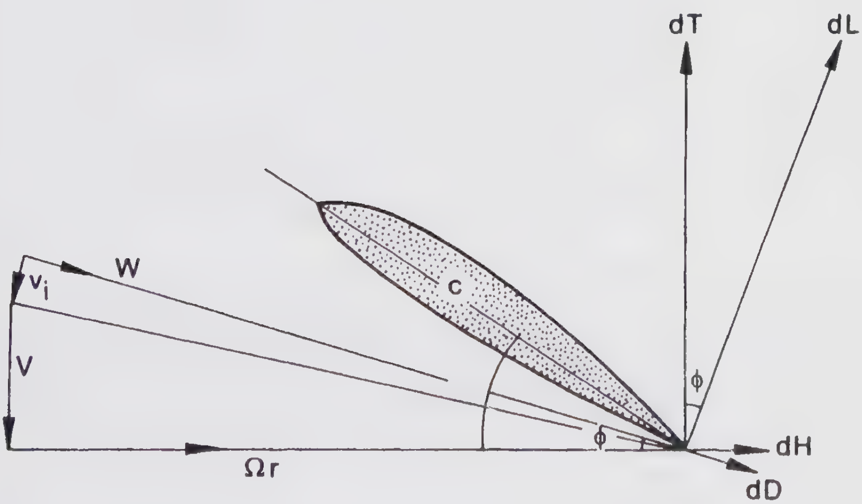


Figure 5.4. Forces and angles of a blade section.

All the variables in these equations are known except v_i . For normal aircraft cruising speeds $v_i \ll V$ and may be neglected in cruising flight. However, for slow speed vehicles like the airship, this is not the case. For practical designs it is acceptable to neglect $(v_i \sin\phi)/\Omega R$ relative to x so simplifying Equations 5.16, 5.17 and 20 to:

$$dL = \tfrac{1}{2}\rho c\Omega^2R^3(x^2 + (J + \lambda)^2)a_1(\theta - \phi)dx \qquad (5.21)$$

$$dD = \tfrac{1}{2}\rho c\Omega^2R^3(x^2 + (J + \lambda)^2)Cddx \qquad (5.22)$$

and,

$$\phi = \tan^{-1}\{(V + v_i \cos\phi)/\Omega Rx\} \qquad (5.23)$$

The thrust T is found from Equation 5.18 by integrating over the length of the lifting blade and multiplying by the number of blades b, remembering that θ and c will most probably be functions of r, that a_1 and C_D are functions of incidence and Mach number and using a guessed value for v_i which might have been determined by using Equation 5.10. The value of v_i is then re-estimated for the new value of T, the final value of which is obtained by iteration. The accuracy of the final result largely depends on the precision with which v_i is estimated. Improved estimation methods for v_i are discussed next.

Once the value of v_i is found Equation 5.19 is used to determine the propeller torque Q. This is found by integrating dH.r over the length of the blade and including any contribution from the non-lifting root section and multiplying by the number of blades b.

It will be noticed from Figure 5.4 that the induced velocity has a component of $v_i \sin\phi$ in the direction opposite to the rotation of the propeller. This is the swirl velocity which represents a loss of propulsive momentum. More heavily loaded fans have inlet and/or outlet guide vanes to minimise this loss.

Propeller performance estimation charts exist which are used to relate thrust and power for a known design. A first approximation for propellers fitted to light aircraft is given by the ESDU data sheets mentioned in the list of references.

Induced Velocity Estimation.

The simple actuator disc approximation may be improved by assuming that the annulus swept by a blade element dr can be treated as an actuator disc producing a thrust b.dT. The equivalent of Equation 5.10 for the annulus at radius r is then:

$$b.dT = 2\rho(2\pi r\, dr)(V + v_i)v_i \qquad (5.24)$$

From Equations 5.21 and 5.24 v_i can be determined. The resulting equation is non-linear unless a further simplification, namely that ϕ is small, is made. For most propellers this assumption cannot be justified. Well established mathematical techniques are used to solve for v_i for each spanwise annulus. The total thrust is then the sum of the contributions from each annulus. The propeller torque is found in a way similar to that described in the last section.

Both the simple actuator disc and the annulus model assume that the two-dimensional lift is maintained out to the blade tip. This is not the case near the blade tip where loss of lift occurs. A simple but moderately effective method of allowing for this loss is to assume that a blade produces no lift outside a radius of BR, where B is a number less than unity. The blade still produces drag in this region and therefore the integration for torque extends to the tip i.e to x = 1.0. Prandtl (1919) derived the following expression:

$$B = 1 - \sqrt{C_T}/b \tag{5.25}$$

where: $C_T = T/\rho A(\Omega R)^2$. Typical values of B are about 0.97.

Prandtl's analysis, which led to Equation 5.25, considered the flow generated by the lifting blades. The lift on the blade is equivalent to a circulation Γ about the quarter chord which is related to the local lift per unit length. This circulation is shed as vortices which trail behind the blade, each vortex moving under the influence of all other vortices. This includes the vortices from the other blades.

Betz (1919) suggested that the induced power of a propeller was at a minimum when the vortex wakes from the blades move axially as if they were a solid screw surface. This hypothesis was later proved by Theodorsen (1948). Prandtl assumed that Betz's hypothesis was correct in which case the induced velocity across the disc would be constant. He further assumed that the curved sheets of the screw surface could be replaced by a series of two-dimensional sheets, based on the premise that the radius of curvature of the outer parts of the sheets is so large that they can be considered as doubly infinite straight strips. Assuming further that the blades have no drag then the element of thrust on an annulus of width dr at radius r is:

$$dT = 2\pi r\rho(V + v_i \cos\phi)2v_i \cos\phi \, dr \tag{5.26}$$

and from the Kutta-Zhukowsky theorem:

$$dT = dL \cos\phi = \rho bW\Gamma \cos\phi \, dr \tag{5.27}$$

where W is the total incident velocity (Figure 5.4). Noting that $W \sin\phi = V + v_i \cos\phi$ (Figure 5.4), eliminating dT between Equations 5.26 & 5.27 gives:

$$v_i = b\Gamma/4\pi r \sin\phi \tag{5.28}$$

The complex potential of the flow produced when the series of two-dimensional sheets hypothesised above move relative to the surrounding air with velocity w is known to be:

$$\Phi + i\Psi = (ws/\pi)\arccos e^{\pi z/s} \qquad (5.29)$$

where Φ is velocity potential, Ψ the stream function, $i = \sqrt{(-1)}$ and $z = x + iy$, the complex variable. The spacing between the vortex sheets, s, is given by:

$$s = (2\pi r/b)\sin\phi \qquad (5.30)$$

The required circulation to maintain the sheet arrangement is given by the difference between the velocity potential immediately above and immediately below the sheet. For simplicity, take the sheet on the x axis, for which $\Psi = 0$, the velocity potential difference a distance 'a' away from the edge gives the circulation Γ as:

$$\Gamma = wsk \qquad (5.31)$$

where:

$$k = (2/\pi)\arccos e^{\pi a/s} \qquad (5.32)$$

k is called the circulation factor. If $v_i = \frac{1}{2}w$, then from Equations 5.30 & 5.31:

$$v_i = b\Gamma/4\pi rk\sin\phi \qquad (5.33)$$

Comparing Equations 5.28 and 5.33 it is seen that representing the finite number of blades has introduced the factor k into the denominator of the expression for v_i. Interpreting 'a' as the distance from the blade tip, R - r, then Equation 5.32 may be written as:

$$k = (2/\pi)\arccos e^{-f} \qquad (5.34)$$

where:

$$f = \tfrac{1}{2}b(1-x)\sin\phi \qquad (5.35)$$

This relation is plotted in Figure 5.5. At the blade tip f = 0 and, as Equation 5.31 shows, $\Gamma = 0$. Increasing the number of blades leads to a larger value of f for a given x and ϕ, which means that the circulation is more nearly equal to the ideal value.

Goldstein (1929) solved the problem without making Prandtl's simplifying assumption regarding the vortex sheets. His analysis implied a certain variation of the inflow angle ϕ with radius which resulted in a more complex expression (actually a semi-infinite series of modified Bessel functions) for k than Equation 5.35. Graphs of k against x for constant ϕ and a value of b may be found in his paper. Lock (1931) extended the range of application by assuming that Goldstein's values of k applied with reasonable accuracy to any practical propeller loading distribution so providing a general method of performance calculation.

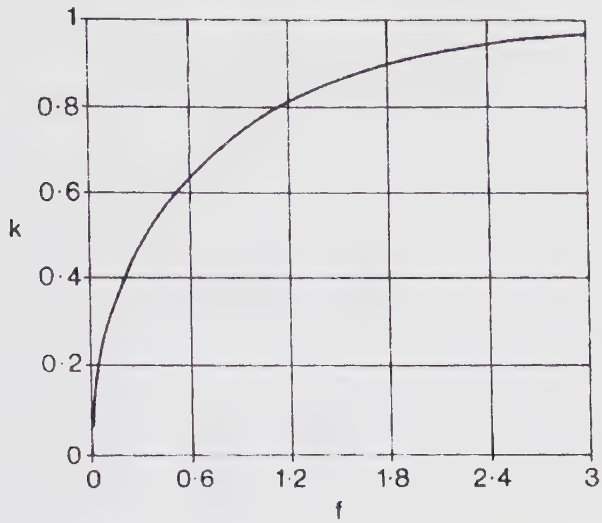


Figure 5.5. Variation of circulation factor k with f.

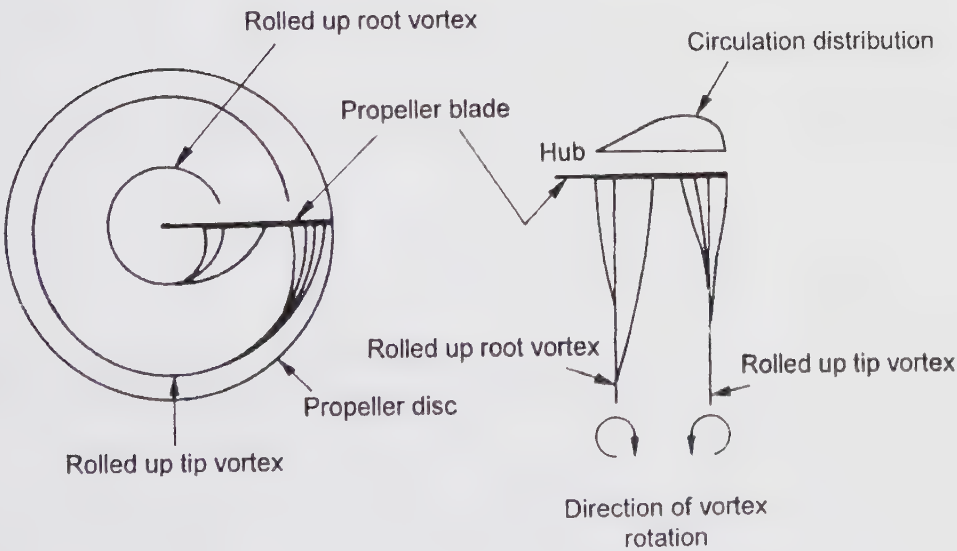


Figure 5.6. Diagrammatic representation of vortex roll-up behind a propeller blade.

The above work may be criticised because it does not include the effect of the wake contraction shown in Figure 5.1. This omission means that the theory is only applicable to light propeller loadings. Theodorsen (1948) made allowance for this effect by starting from the final contracted wake and calculating the ideal propeller which generates it. Theodorsen (1969) extends the method to static propellers.

These methods all assume that the shape of the vortex wake is fixed and is described by the parameter s. Such analyses are called, for obvious reasons, 'fixed wake models'. The wake can also be conceived as a series of vortices springing from the trailing edge of a blade, the strength of each vortex being determined by the change in bound circulation each side of the point of origin. Each vortex will move under the influence of all other vortices with the exception of the bound vortices on the blade. Within a short distance behind the blade the vortices move towards the tip and the root region where they combine to form two concentrated vortices which trail behind and below the propeller. This is shown diagramatically in Figure 5.6. The root and tip vortices do not stop as shown in the left hand diagram but continue to contract and move downwards. For clarity only the first circuit has been shown. The bound circulation is approximated by a series of constant values as shown in Figure 5.7 and the trailing vortices are broken into straight segments. The velocity which any one of these vortex segments induces at a point P is given by the Biot and Savart law:

$$dV = \frac{\Gamma \cos \beta \, ds}{4\pi \, r^2} \tag{5.36}$$

where the symbols are defined in the inset in Figure 5.7. In this example dV at point P is normal to and points into the plane shown. The position of each segment is obtained by iteration. Methods to speed up the convergence have been developed, in particular the choice of the initial positions of the vortex segments. For more details readers are advised to consult papers by Langrebe and his co-workers, for example Langrebe (1971).

Propeller Performance - A Comparison of Theory and Practice

Propeller performance is measured on a test stand, usually in the open air, for static conditions. The main problem is obtaining very low wind conditions in which to make the measurements. Forward speed tests are made in a wind tunnel. The maximum size of propeller which may be tested is determined by the size of the working section or the size of the airstream in a blower tunnel. For closed working sections the walls must be sufficiently far away so that they do not affect the flow at the propeller. For closed circuit wind-tunnels the energy put into the airstream must be distributed throughout the full flow before it re-enters the working section. If not the test is equivalent to a propeller operating in a distorted entry flow. If these conditions are satisfied the propeller area is restricted to less than 20% of the working section area.

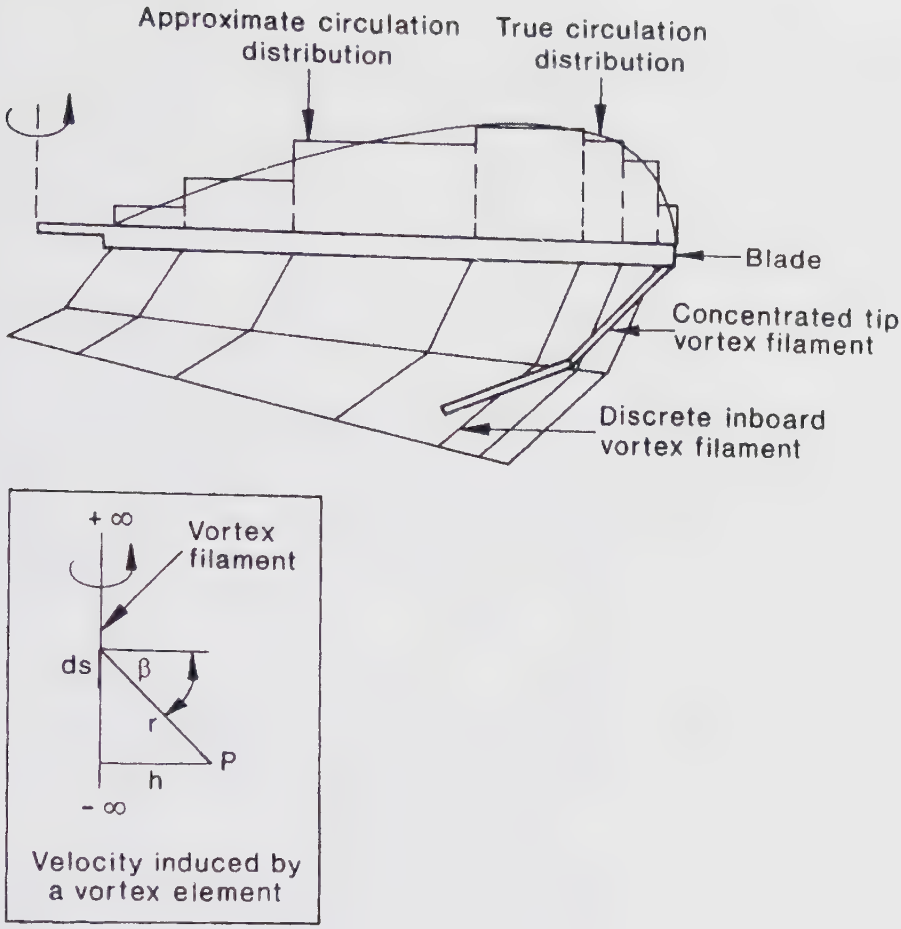


Figure 5.7. Vortex wake modelling behind a lifting blade.

Results from propeller prediction and test are usually presented in non-dimensional form. These are the thrust C_T and power coefficient C_P where:

$$C_T = T/\rho n^2 d^4 , \quad C_P = P/\rho n^2 d^4$$

Here n is the number of revolutions per second and d the propeller diameter. The efficiency η is defined by $\eta = TV/P = C_T J/C_P$ where $J = V/nd = V/\Omega R$. The blade activity factor AF is a measure of the solidity which is the ratio of the total blade plan area to the disc area. It is defined by:

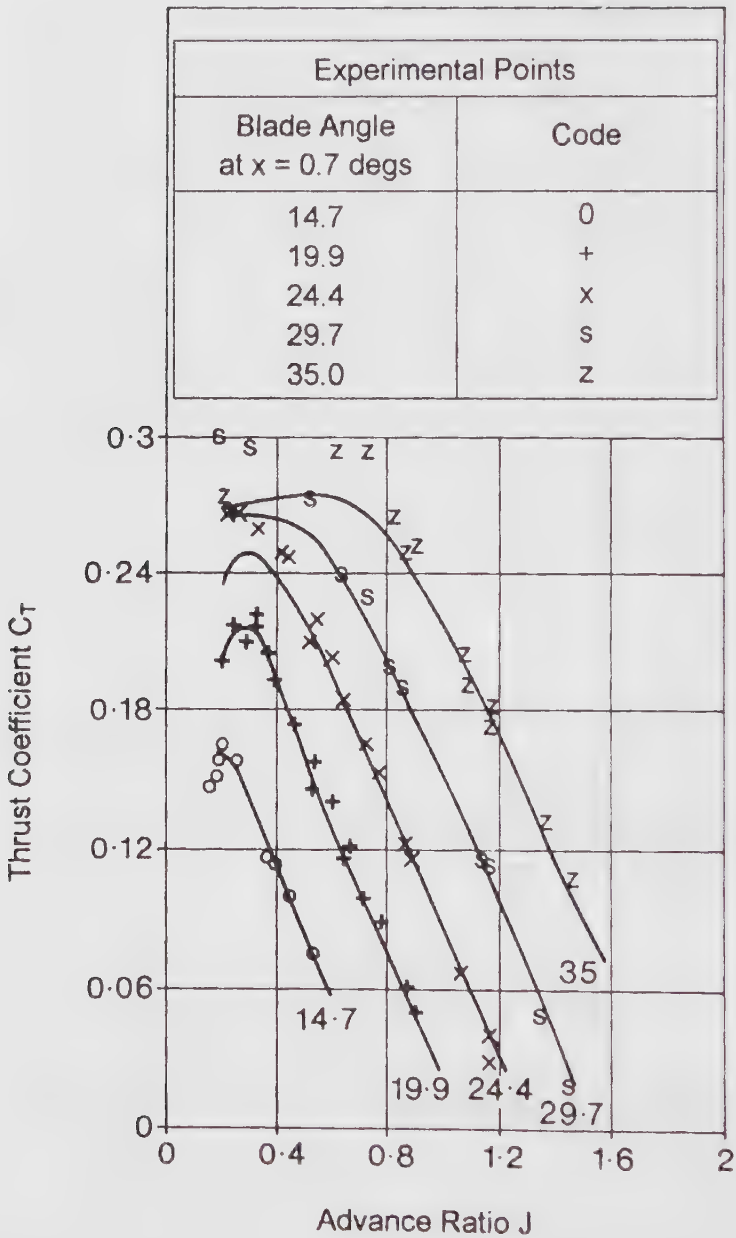


Figure 5.8. Full scale propeller wind tunnel test results C_T vs. J.

$$AF = \frac{100\,000}{16} \int_0^1 \frac{cx^3 dx}{d}$$

Activity factors are normally in the range 100 - 150 for aircraft propellers. The pitch of a propeller, p, is the distance it would advance in one revolution if there were no slip. From Figure 5.4 it may be seen that $p = 2\pi R\ .\tan\theta$. For a constant pitch propeller of diameter D the section pitch angles are calculated from:

$$\theta = \tan^{-1}\{(p/D)/\pi x\}$$

A typical comparison of theoretical and experimental results is given in Figures 5.8 & 5.9. These results are quoted from data supplied by Paul Methuen of Dowty Aerospace Propellers.

Figure 5.8 shows the comparison of strip theory with experimental result obtained in the RAE 24 foot open jet wind tunnel with a full scale 2.77 m four-bladed propeller. The curves are for different blade pitch settings defined by the value at 0.7 radius denoted as $\theta_{0.7}$. The results shown are for the thrust coefficient C_T against the advance ratio J. The strip theory curves were derived by calculating the thrust at measured powers.

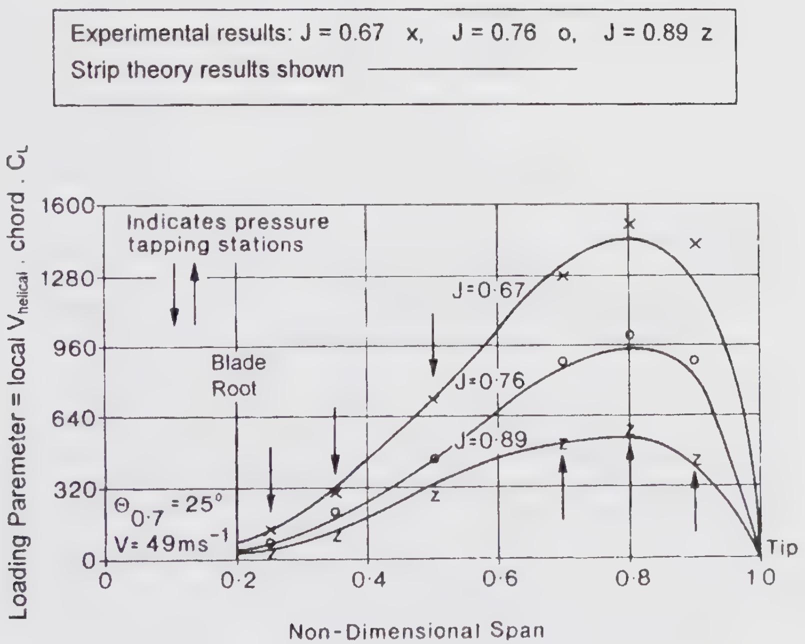


Figure 5.9. ¼ scale four bladed pressure tapped propeller measurements.

Agreement is good except at high values of C_T, at lower values of J and for the higher values of $\theta_{0.7}$. This is the region of the performance map where stall will occur and work is in hand to improve predictions of three-dimensional stalling characteristics.

Figure 5.9 shows the results obtained in the Southampton University 11 x 8 foot wind tunnel from a 0.69m diameter four-bladed propeller. From chordwise pressure measurements made at six spanwise locations the loading parameter (lift) has been derived for three advance ratios. J was changed by varying the rotational speed of the propeller at a fixed tunnel speed of $49ms^{-1}$. The loading parameter has also been estimated by strip theory and this is shown by the continuous curves. The comments on agreement made on Figure 5.8 above also apply here.

Ducted Propellers.

Consider the open propeller represented in Figure 5.1 and enclose it in a duct as shown in Figure 5.10.

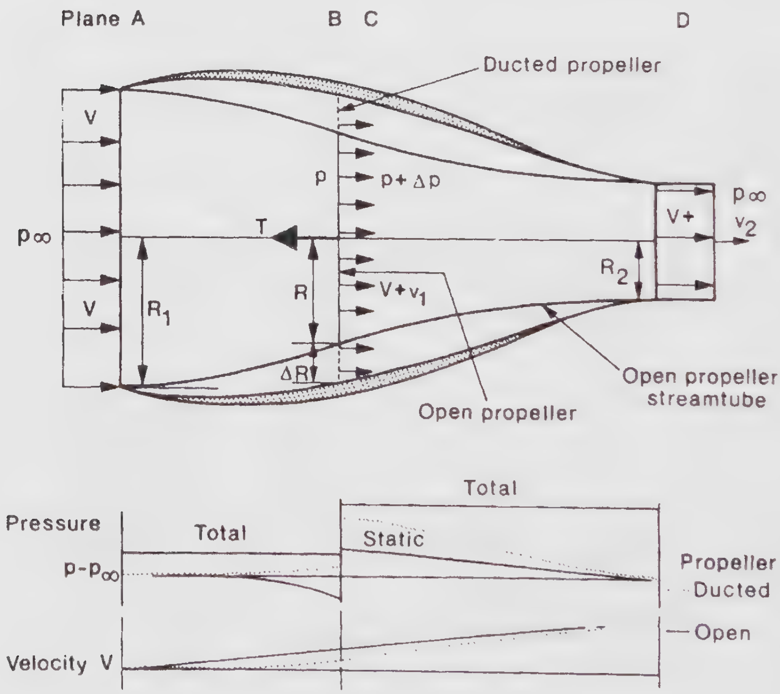


Figure 5.10. Comparison of an open with a ducted propeller.

The duct is chosen so that upstream at plane A and downstream at plane D the flows are identical. Both propellers will produce a pressure rise Δp across their respective discs. Thus the resultant thrust of both systems must be the same since the rate of change of momentum is the same. If Q is the mass flow at any plane of either system then the total thrust T is given by:

$$T = Q((V + v_2) - V) = Qv_2 \tag{5.37}$$

The thrusts produced at the propeller, T_P, and the ducted propeller T_D are:

$$T_P = \Delta p\, \pi R^2 \tag{5.38}$$

and,

$$T_D = \Delta p\, \pi(R + \Delta R)^2 \tag{5.39}$$

respectively. However T_P must equal T but T_D must be combined with any thrust which is produced by the duct. Subtracting Equation 5.38 from 5.39 gives the thrust produced by the duct, in this case in a negative direction, as:

$$T_{duct} = -\Delta p 2\pi R.\ \Delta R = -T_P\, 2\, \Delta R/R \tag{5.40}$$

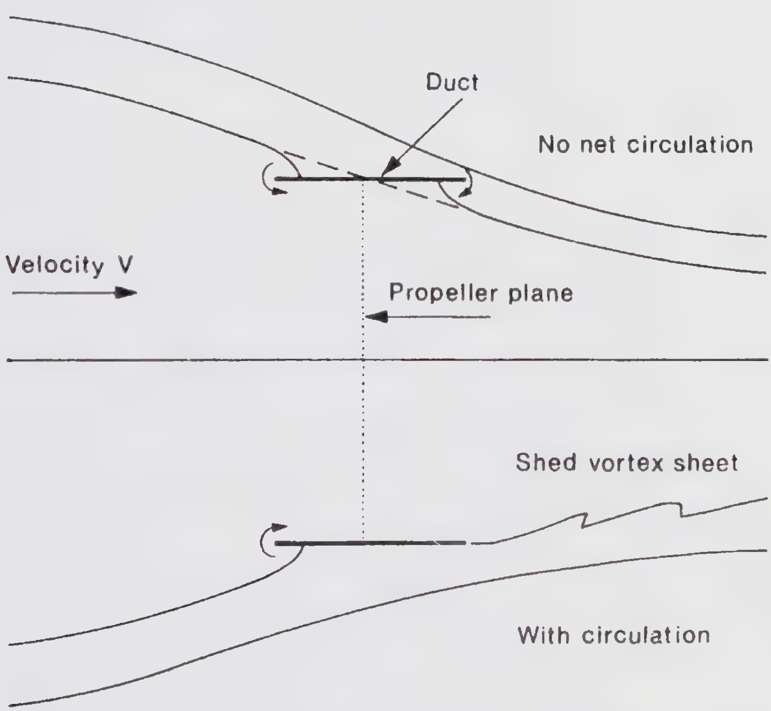


Figure 5.11. Effect of simple duct on flow about a propeller.

Although the pressure rise across the two discs is identical, the velocity through the two discs will not be the same, the velocity through the larger ducted disc being the lower. Bernoulli's equation between planes A and B shows that the static pressure at plane B is higher for the ducted case. The comparative pressures and velocities for the two flows are also shown in Figure 5.10.

Figure 5.11 shows the way in which the force is generated on the duct. The upper half of the diagram shows a propeller and two streamlines (solid curves). A simple cylindrical duct is inserted and this alters the streamlines (dashed curves). The flow adjusts around the leading and trailing edges where equal and opposite suctions are produced. There is no net circulation around the duct. However in practice the situation is that shown in the lower half of Figure 5.11. The Kutta condition must be satisfied at the trailing edge and the leading edge of the duct must be rounded to avoid a velocity discontinuity. Thus the surface at the leading edge now supports a suction due to the accelerating flow around it so giving rise to a thrust force while the flow from the trailing edge will result in a time-dependent and possibly periodic shedding of vorticity. This is the boundary of a jet. In the case when the pressure at the outlet plane is equal to p_∞ a steady vortex sheet will be formed.

The development of circulation suggests that the duct may be modelled as a distribution of ring vortices along its camber line. The strength of the vortex rings is chosen so that the resultant flow from the free stream, the propeller and the vortices is tangential to the duct surface at a number of points equal to the number of vortex rings. The simplest model is by Weissinger who used a single vortex ring situated at the quarter chord of the duct. The strength of this vortex is determined by making the resultant flow tangential to the duct at the three-quarter chord position. The geometry of the model is shown in Figure 5.12.

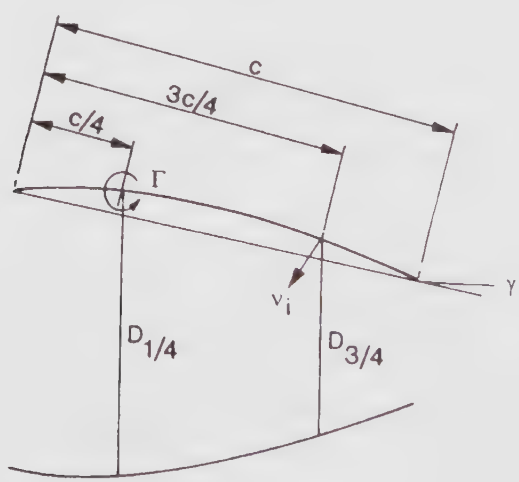


Figure 5.12. Approximation to a ring aerofoil.

The induced velocity v_i is found from:

$$v_i = \frac{\Gamma}{\pi D_{1/4}} f\left(\frac{c}{D_{1/4}}, \frac{D_{3/4}}{D_{1/4}}\right) \tag{5.41}$$

where the function **f** arises from the integration round the vortex ring to give the velocity at any point on the three-quarter chord circumference. Values of the function **f**, taken from Küchemann and Weber (1953), are shown in Figure 5.13. To complete this calculation it is necessary to determine the radial velocity variation of the propeller flow as a function of axial distance.

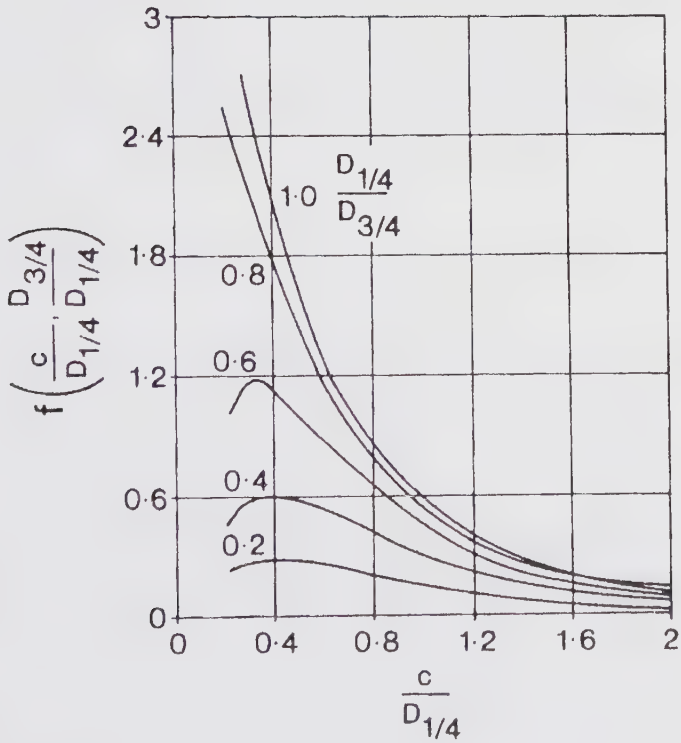


Figure 5.13. Variation of 'f' with ring aerofoil parameters.

This is most simply done by approximating the propeller wake as a single tip vortex helix the geometry of which is shown in Figure 5.14. Let p be the pitch of the helix with generating angle θ and the differential element of the vortex ds be located by the radius vector **R** from the origin. For the point z_p, the radius vector **r** to the vortex element is given by:

$$\mathbf{r} = \mathbf{i}R\cos\theta + \mathbf{j}R\sin\theta + \mathbf{k}(p\theta/2\pi - z_p) \tag{5.42}$$

where **i**, **j** and **k** are the unit orthogonal vectors. So ds = $(-\mathbf{i}R\sin\theta + \mathbf{j}R\cos\theta + \mathbf{k}p/2\pi)d\theta$ as it is orthogonal to **R**. Using the Biot and Savart law, the axial velocity v(z) induced at z_p for a vortex of strength γ is:

$$v(z) = \frac{\gamma}{4\pi}\int_0^\infty \frac{-r x ds}{|r|^3} = \frac{\gamma}{2p}\left\{1 + z_p / \left(R^2 + z_p^{\,2}\right)^{0.5}\right. \tag{5.43}$$

The variation of v(z) may most easily be expressed as:

$$\frac{v(z)}{v_i} = 1 + \frac{z/R}{\sqrt{(1 + (z/R)^2)}} \tag{5.44}$$

where v_i is the induced velocity at the propeller disc, z = 0.

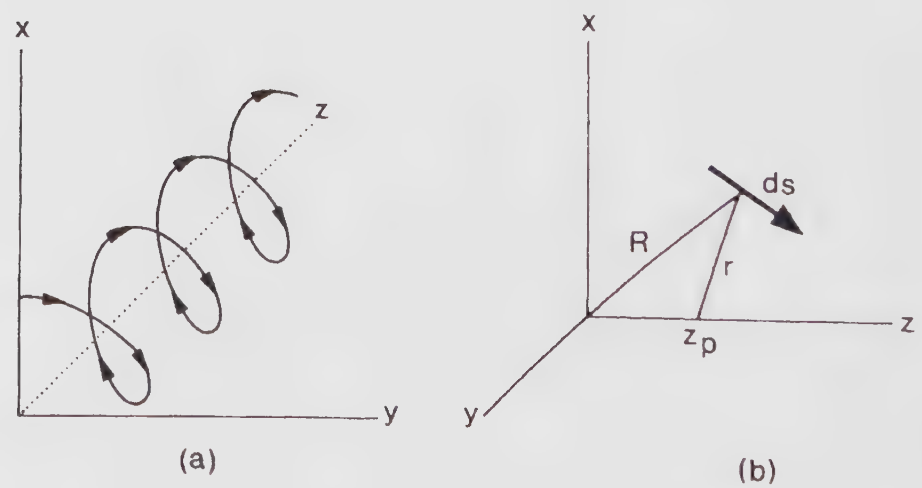


Figure 5.14. Geometry of a helical vortex.

Using the continuity condition:

$$(V + v_i)\pi R^2 = (V + v(z))\pi R_z^2 \qquad (5.45)$$

where R_z is the radius of the streamtube at z. The slope of the streamtube is given by:

$$dR_z/dz = -R(dv(z)/dz)/2(V + v(z)) \qquad (5.46)$$

and the radial velocity v_{iR} is:

$$v_{iR} = (V + v(z))\, dR_z/dz \qquad (5.47)$$

Combining Equations 5.44, 5.46 and 5.47, with Equation 5.10 providing the value of v_i, the information is available to find the thrust of the duct using Weissinger's approximation. If Θ is the tangent to the mean camber line at 3c/4 then:

$$(-v_{iR}(3/4) - v_i)/(V + v(3/4)) = \Theta \qquad (5.48)$$

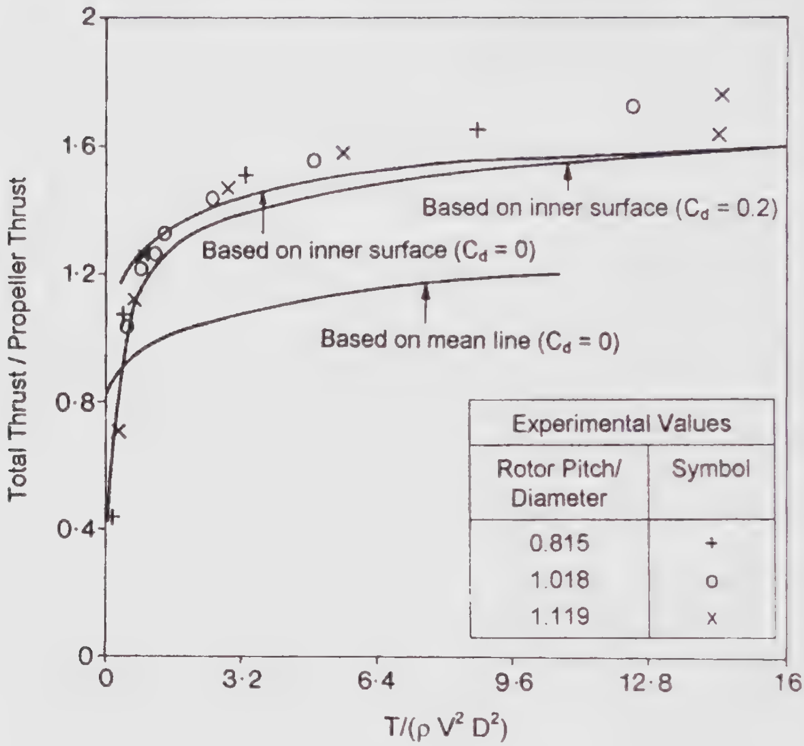
where R(3/4) and v(3/4) are the values of the variables at the 3c/4 plane. Equations 5.41 and 5.48 allow v_i to be eliminated and Γ determined from:

$$\Gamma = \{\pi D_{1/4}/\ f(c/D_{1/4}, D_{3/4}/D_{1/4})\}[-v_{iR(3/4)} - \Theta\,(V + v(3/4))] \qquad (5.49)$$

The duct thrust T_p is then:

$$T_p = -\rho v_{iR}(1/4)\, \Gamma\pi D_{1/4} \qquad (5.50)$$

The duct can increase thrust and thrust/power ratio particularly at zero forward speed, but its drag is not negligible. This is particularly true if a duct is designed to enhance static thrust. The drag of the duct may be estimated in the standard manner. An indication of the accuracy of this estimation method and the effect of duct drag is shown in Figure 5.15 which is taken from McCormick (1967). The duct shape and position of the propeller is also shown in that Figure. The continuous lines show the estimated performance using both the inner duct surface contour and the mean camber line to determine the duct circulation Γ. The abscissa of the graph is a form of thrust coefficient based on the total thrust T. The use of the inner duct contour is much superior. The inclusion of duct drag is of greatest importance for low thrust conditions. For higher thrust coefficients an underestimate of the thrust ratio results. However, agreement is reasonable bearing in mind the simplicity of the mathematical model. It suggests that a more representative model using sources for thickness effect as well as a distribution of vortices will give better agreement. Such a model will only be correct if the flow stays attached to the duct both internally and externally; failure to do so will probably result in a poorer performance than that of the isolated propeller.



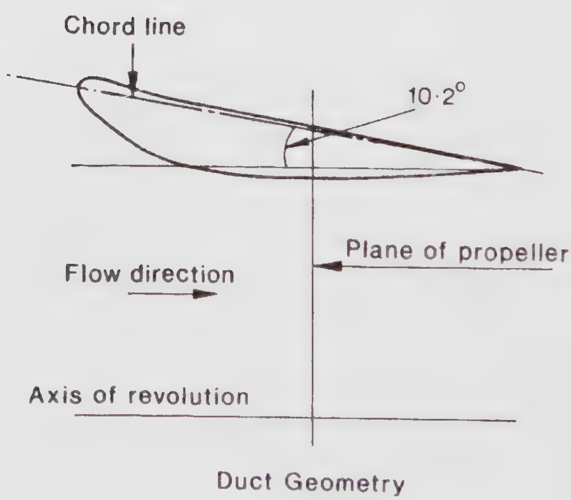


Figure 5.15. Ducted propeller performance.

Ducting a propeller may also have operational advantages by offering protection to people when the airship is on the ground, offering some protection to the propeller from trailing lines and ground vehicles and allowing the installation of acoustic liners to reduce external propeller noise. For heavily loaded propellers the installation of inlet, and possibly outlet, guide vanes will reduce swirl and enhance the performance.

THE PRIME MOVER

The extraction of energy from added fuel and its conversion to a form which can do useful work is described by a number of thermodynamic cycles. Three cycles dominate currently used prime movers. These are the Otto cycle used by the reciprocating, spark ignition internal combustion engine (abbreviated to ICE), the Diesel cycle of the compression ignition ICE and the Joule (in the UK) or the Brayton (in the USA) cycle for the gas turbine ICE. The basic cycles are not described here but may be found in all basic propulsion texts. The choice of the prime mover is influenced by the overall cost. This includes the initial cost, the running cost which incorporates maintenance expenses and fuel as well as the effect of the weight on the payload which can be carried. Choice also depends on the availability of an engine in the correct power range unless the project is able to bear the cost of the development of a dedicated unit. In this chapter the discussion will concentrate on the basic characteristics of engines which use the three principal cycles. The variation of shaft speed and specific fuel consumption (SFC) with power for the three cycles is shown in Figure 5.16.

Comparative Performance

The relation between power and shaft speed is a discrete curve as shown in Figure 5.16. The specific fuel consumption as a function of power depends on the size of the engine, the larger units achieving a thermal efficiency of 30% but the smaller engines only reach 20%. The SFC is shown as a band in each case. The maximum power does not coincide with lowest specific fuel consumption in the case of the Otto and Diesel cycles. The SFC of the three cycles is in order of improving performance, the Joule, the Otto and the Diesel. Figure 5.17 shows the variation of engine specific weight with shaft horsepower as a shaded band for shaft turbine engines. There are insufficient modern Diesel and Otto cycle aircraft engines in production to produce similar curves for them so some examples are shown as discrete points. The Joule cycle gives the lightest and the Diesel the heaviest engine. It is essential to consider the combined engine and fuel used weight in typical missions to decide the preferred engine type(s).

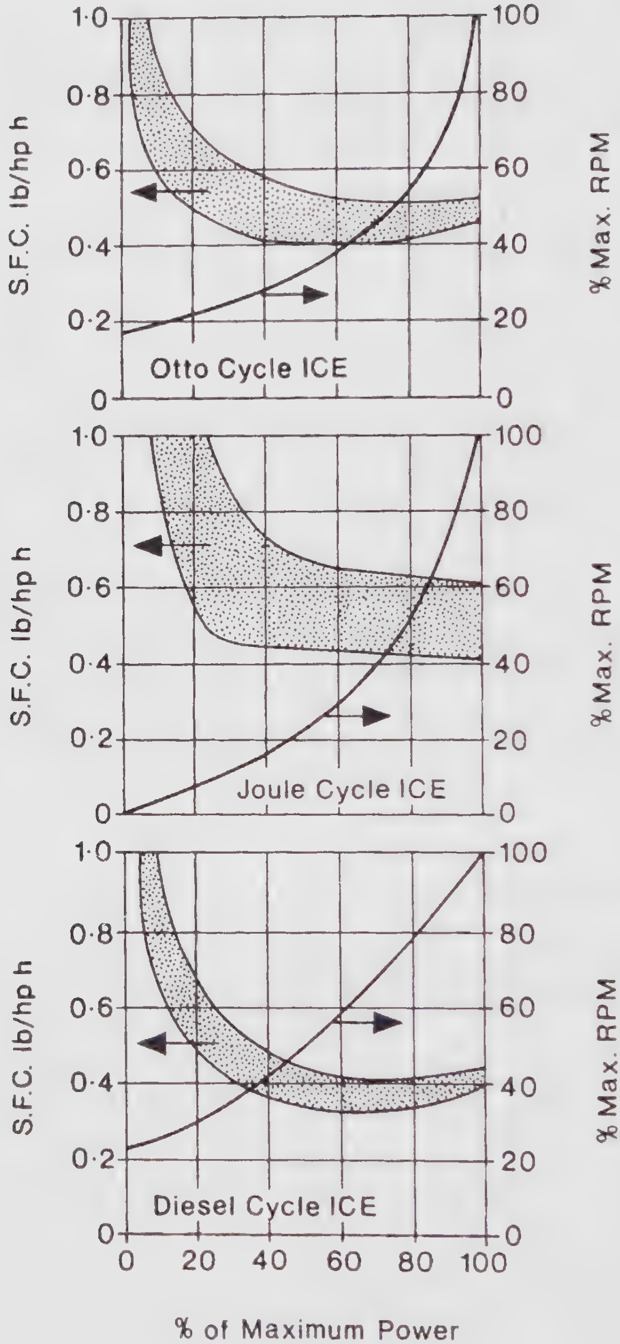


Figure 5.16. Variation of specific fuel consumption (SFC) with power for the main types of ICE.

The missions which are normally cited as being especially suitable for airship operation take advantage of the excellent loiter characteristics of buoyant lift. Various authors have discussed these roles and readers are referred to the papers presented at the 18th Annual Symposium of the Airship Association and reported in 'Airship' No. 98 for a balanced discussion. In one of those papers Hillsdon (1992) succinctly summarised the conflicting factors when choosing an airship propulsion system. The following is a quotation from that paper.

"The endurance of an airship is governed by the difference between permitted heaviness at take-off and permitted lightness at landing. The only way out of this constraint is reballasting during flight.

Reballasting in flight involves either pick-up from the surface (possibly incompatible with many surveillance roles) or recovery of ballast water from engine exhaust. The latter course is extremely difficult with gas turbine engines and is deleterious to fuel consumption with any engine.

At low flight speeds, power for propulsion may well be exceeded by the power loading of the surveillance mission equipment and essential services. The engine efficiency of installed systems is thus paramount for the airship.

An overall energy balance must be computed for all the mission profiles projected for the airship and used together with the appropriate spectrum of winds for the operating areas to evolve an overall power spectrum for the ship."

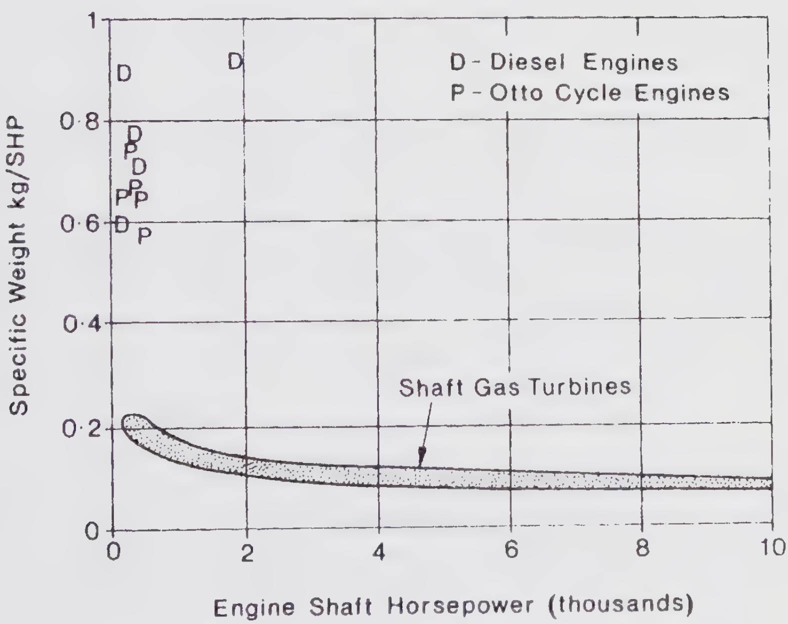


Figure 5.17. Engine specific weight vs. shaft horsepower.

These requirements determine the power units which meet the basic power demands of the missions. The third point above states this will be determined by the speed requirements and the provision of services for the operation of the craft and its payload. Thus electricity generation, provision of hydraulic power etc. required to power ballonet inflation fans, control surface actuators, cabin conditioning as well as surveillance radars, winches etc. for the different roles have all to be assessed for their part in determining the base load. This power must be provided most efficiently. For the larger airships part of the base load will be provided by an auxiliary power unit which is run at a constant speed to give optimum fuel efficiency.

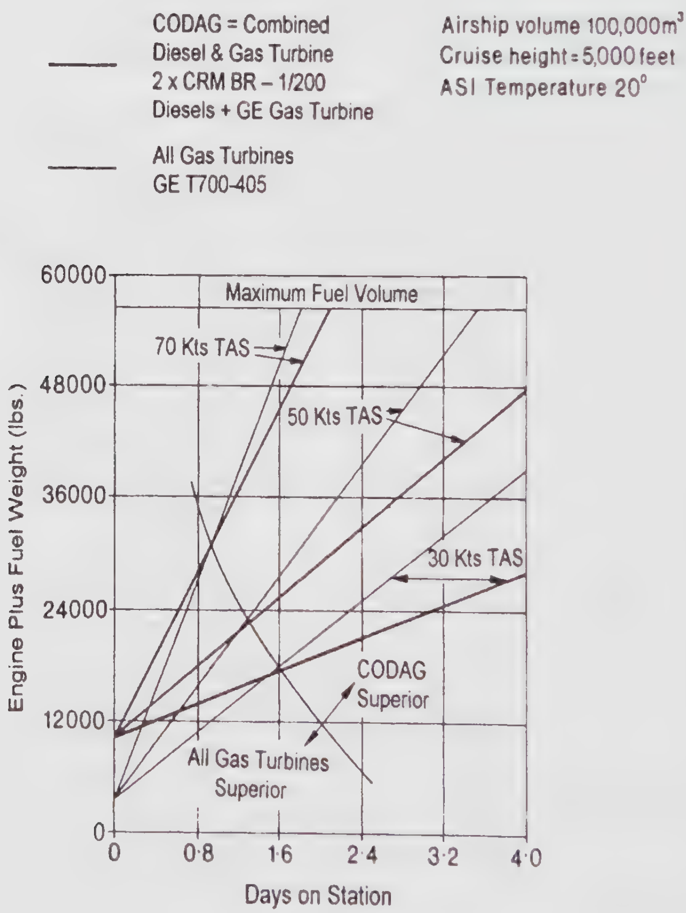


Figure 5.18. Endurance comparison of a CODAG and an all gas turbine solution.

The problems following an engine failure must be considered against the role requirements. If it is essential that the mission continues after the loss of an engine then either the remaining engine(s) can be run at higher power settings or a spare engine can be started and its output added to replace that of the failed unit. In the latter case the mission can continue as planned but all operations will pay the penalty of having to carry the weight of the 'spare' power-plant as a loss of payload. In the case of the YEZ-2A this solution was adopted with the stern turbo-prop unit only being used for specific phases of the flight, like a high speed dash, or an emergency. The choice of the lighter, but slightly thirstier, turbo-prop unit for this role compared with the Diesel main engines demonstrates the compromise which the designer has to make. Such a choice carries with it the need to provide technical and maintenance support for both types of engine as well as two types of fuel supply unless the gas turbine is adapted to burn diesel fuel or the diesel JP4.

The benefits of the YEZ-2A CODAG (COmbined Diesel And Gas turbine) power-plant installation relative to an all gas turbine installation can be demonstrated by calculating the endurance of two identical airships apart from their power plants. Figure 5.18, copied from an article by Hillsdon (1986), shows the time at which the better fuel consumption of the CODAG system overcomes its heavier installation weight when compared to an all gas turbine drive system. The endurance varies with the operational airspeed required, the higher the speed the greater the power needed and, therefore, the sooner the CODAG system becomes superior. The choice of the CODAG installation for the long endurance missions intended for the YEZ-2A is demonstrated. Figure 5.18, however, also shows that for short range passenger and freight operations, for which the higher airspeed but relatively short endurance is likely to be the norm, the all gas turbine installation will probably be preferred.

The larger the lifting capacity of the airship the greater is the choice of propulsion arrangements. The advantage, however, of keeping the number of engines and propulsors to a minimum commensurate with operational requirements - including safety - is no different from that for other types of airborne vehicles. The arrangement and choice of the propulsion system can play an important role in airship control and may improve the overall aerodynamic performance. This is considered in Chapter 3.

ENERGY SOURCES

Since lift from buoyancy is constant at a fixed temperature and pressure, an airship will climb as fuel is consumed unless other means are used to trim the craft. The Graf Zeppelin was fuelled with a mixture of propane and hydrogen which has a density very similar to air. As the fuel was consumed it was replaced by air so keeping the craft weight approximately constant.

The characteristics of various fuels which have been considered suitable for aviation use are shown in Figure 5.19. The points show the volume and the weight required to produce a unit heat release relative to that for kerosene. Clearly fuels which lie to the left and below the **o**, which marks kerosene itself, are desirable. Those shown in the diagram are boron based from which toxic by-products result so for general use they may be discounted. Hydrogen stands out as being of special interest due to its low weight per unit heat release however it must be remembered that the container for hydrogen is expensive, heavy and large relative to a normal aviation fuel tank. No concept design of a hydrogen fuelled airship relative to a conventional layout exists. To gain some indication of the gains and losses, results from a Lockheed study which compared a 1011 airliner using JP4 with a variant using hydrogen fuel to perform the same mission are given in Table 5.1. The figures show that for the hydrogen burning aircraft the take-off weight and that of the fuel is reduced, but that the fuel volume is increased. This reduces the lift/drag ratio significantly. It is however concluded in the study that hydrogen fuel would be an acceptable alternative to oil based fuels if the latter became in short supply. On this basis one would expect hydrogen fuel to be a useful source of energy for airships.

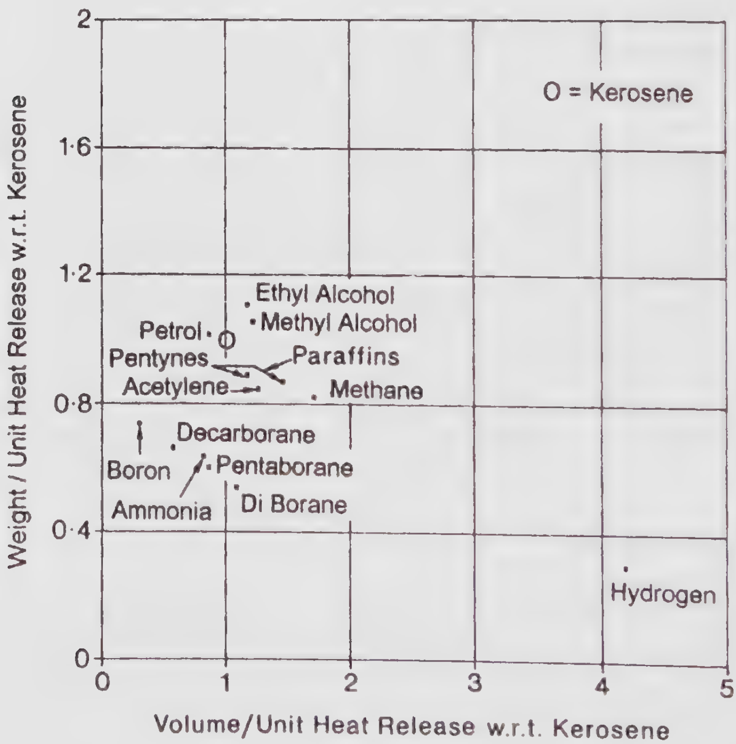


Figure 5.19. Weight and volume per unit heat release w.r.t. kerosene.

If a safe method of containing it in gaseous form could be found, its use to increase buoyancy in particular phases of the flight would be a further bonus for the airship. Recent, but unconfirmed, reports suggest that a Russian airship prototype, the ALA600 developed by the Moscow Aviation Institute, is to be fuelled with hydrogen which will both provide buoyancy and be burned in the turbo-prop engines. For the immediate future, however, conventional hydrocarbon fuels appear likely to be the norm.

PROPULSION, PERFORMANCE AND CONTROL

The quotation in the section on ***Comparative Performance*** relating the influence of heaviness to the choice of the propulsion system did not include in the potential solutions the use of engine generated thrust. The Airship Industries series of airships have demonstrated that vectoring the thrust of the propulsion engines improves both the performance and the control of the craft. In those airships the pitch of the ducted propellers is reversible so enabling relatively rapid changes in thrust. In addition the ducted propeller can be rotated from 90^{o} up to 120^{o} down so enabling the thrust line to be directed for both performance and control reasons.

In a vectored thrust design the mechanical arrangement of engine(s) and propeller falls into one of two basic classes. The engine can drive the propeller directly in which case it rotates as the thrust is vectored. The engine lubrication and fuel supply must then be designed to operate for extended periods in an inclined position. Most engines are not designed for such extended operation and the cost of the modification, when only a small number of engines are required, is high.

Table 5.1. *Comparison of a conventional with a hydrogen fuelled Lockheed 1011 transport aircraft*

Aircraft Fuel	**JP4**	**Hydrogen**	**% Change**
Gross Wt. lbs.	430,000	318,000	-26
Op. Empty Wt.	239,200	215,350	-10
Fuel Wt. lbs.	137,000	46,650	-65.9
Fuel Vol. cu. ft.	2,920	11,050	+278
Wing Area sq. ft.	3,460	2,830	-18.2
L/D	15.5	12.6	
SFC lb./lb. h	0.677	0.216	

The inertia of the rotatable propulsion unit is significantly increased so requiring larger control actuators. Fuel and engine control signals have to be provided through a rotating joint. The alternative is to mount the engine(s) in the non-rotating frame of reference and transmit the drive through a right-angled gearbox to the propeller with a consequent weight, performance and maintenance penalty.

The trend is to accept the penalty of a right-angled gearbox and mount the engines on or in the gondola of non-rigid airships. In symmetrical propeller arrangements, as in the Skyship airships, this allows the designer the further option of interconnecting the propellers with a transverse shaft on to which all engines drive through free-wheels and/or clutches so enabling both propellers to produce thrust in the event of an engine failure.

A method of increasing the deflection of the propeller slipstream, so reducing the mechanical tilt needed, has been adapted from tilt-wing experience. Nayler (1988) describes the method proposed by Advanced Airship Corporation for the ANR airship which was under construction in the Isle of Man. The stub wing attached at the rear of the gondola, which has a propeller and engine at each wing tip, can be rotated from 75° up to 30° down. The deflection of the slipstream may be increased to an equivalent of 90° by the deflection of a single trailing edge flap. Beyond the end of the wing the slipstream deflection due to the trailing edge flap is much reduced.

The non-rigid airship design restricts the mounting of the propulsors to the gondola since this is the only structure which can readily dissipate the thrust throughout the whole craft. The designers' scope for influencing the aerodynamics of the whole vehicle by the air flow through the propulsors is therefore limited.

The rigid or semi-rigid design has more flexibility, the range of possible mounting points being illustrated in photographs of the Zeppelin and US designs. Positioning a propulsor at the tip of the tail cone has two advantages. First it ingests the boundary layer which has developed along the hull. Equation 5.12 above shows that as V, the incident velocity on the propulsor, decreases the power required per unit thrust decreases. (The thickness of and momentum loss in the boundary layer is discussed in Chapter 3). Secondly the propulsor entrains the flow around the hull which accelerates the boundary layer, thus reducing the risk of flow separation. This reduces the profile drag of the hull but will have little effect on the more important skin friction drag. By itself this gain is unlikely to justify the complication, weight and moment of inertia increase which will result. For further discussion of the ingestion of boundary layers into a power-plant readers are referred to Küchemann (1978), page 315.

The tail mounting of a propulsor can, however, provide considerable control advantages if its thrust is vectored. This may be done by moving the propeller axis of rotation to provide pitch and/or yaw control. Such a system is described by Kollmann (1992) for the projected Zeppelin NT. Alternatively, control surfaces (rudders and/or elevators) mounted behind a fixed axis propeller may be inclined to deflect the slipstream. While this is mechanically more simple than swivelling the propeller its efficiency is lower due to the drag of the surfaces as well as their weight penalty.

There has been much talk of copying ships and installing bow and/or stern thrusters for low speed control. Advanced Airship Corporation's ANR airship was planned with both bow and stern thrusters. These were low velocity cold air jets which could be vectored to provide pitch and/or yawing moments and vertical and/or sideways forces. Actuator theory has shown that to maintain an acceptable efficiency such jets must obtain their rate of change of momentum by using a large mass flow exhausting at a low velocity. Nayler(1988) described the system as follows.

"The low-velocity jet produces a minimum thrust of 27kg. and a volume flow *of 160* m^3*/min. Ballonet air is used as the supply reservoir boosted by two fans The air passes to the plenum chamber and thence to one pitch and two yaw ducts. With the fans running stalled, thrust is immediately available when a duct valve is opened.*

This system will assist control at low airspeed (< 10 knots) and during the hover."

Such a system avoids the complication of placing a fan at the thruster which could be difficult mechanically. It also provides a large reservoir of pressurised air which is maintained by the fans which each have the same maximum volume flow as the jets.

The reduction of drag by the use of controlled blowing or suction has been actively researched for many years but has not yet found a practical application. One approach of considerable interest to the airship designer is to delay the boundary layer transition region so reducing skin friction drag. For this application suction is used to remove most of the boundary layer. Suction may be applied beneath a porous skin. Varying the porosity of the skin to reflect the potential growth of the boundary layer over a particular area allows a constant suction pressure to be applied. A major problem is the small size of the pores which makes them very vulnerable to becoming blocked by insects or general atmospheric dirt. An alternative approach is to use slots across the flow direction into which the boundary layer, which has developed from the upstream slot, is sucked. This solution, while more tolerant of dirt, brings mechanical problems. The maximum suction pressure is 1 bar. Large ducts are needed to remove the 'dead' air which in the case of the airship represents a buoyancy penalty. For both systems vacuum pumps are required and these must be powered from the engines.

Injection of momentum into the boundary layer by blowing through a surface slot will not produce a laminar boundary layer. It is effective in delaying separation by re-energising the boundary layer. Since high pressure air may be used up to the slots the internal ducts are smaller than for the suction system. High pressure air is available from gas turbines, up to 10% of the compressor mass flow may be bled away. While this reduces the power output of the engine it does avoid the installation of more engine accessories.

Suppressing separation allows the designer to use a hull shape which has a higher thickness ratio and is structurally better. Paki and Pipitone (1975) have made calculations and wind tunnel experiments on such a shape using a radial suction slot at the rear. Figure 5.20 shows the shape of their test body as well as the velocity profile. They have achieved accelerating flow almost up to the position of the slot so reducing the growth of the boundary layer. The slot suction permits the freestream flow to turn the sharp corner at the junction with and to remain attached over the short tail cone. A simple design exercise on an airship with a volume of 10^6 cubic feet suggested an endurance improvement of between 20 and 40% at most operating speeds. One interesting idea was to exhaust the flow taken in through the slot through a swivelling nozzle at the tip of the tail cone so providing enhanced low speed control. While an interesting concept, it requires further detailed study and some flight experience to confirm the advantages claimed for boundary layer control.

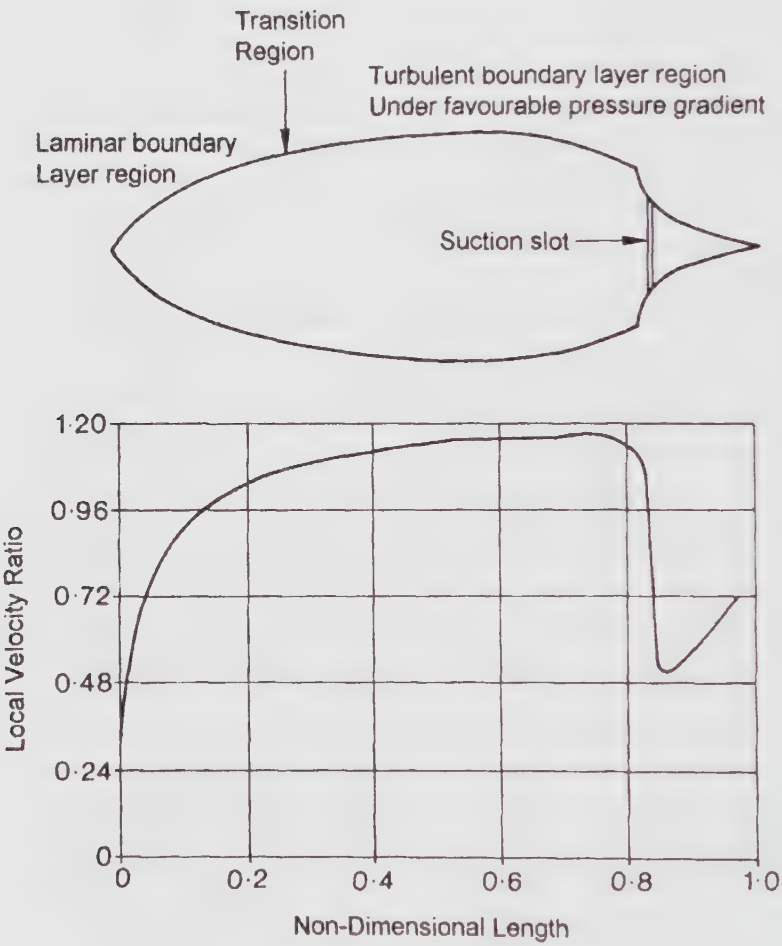


Figure 5.20. Velocity ditribution over BLC airship body shape.

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6

Materials

P. Bradley

INTRODUCTION

Many of the major material developments of this century, particularly in the areas of specific strength, have been instigated by the aerospace industries. These developments/advances have fundamentally changed the design of aircraft. The introduction of such materials as lightweight strong alloys, fibre reinforced composites or honeycomb materials have all had major impacts on the design of aircraft structures while improvements in high temperature properties through alloy development and manufacturing methods (e.g. directionally cast, single crystal, or metal matrix composite turbine blades) have transformed engine technology.

Most of these developments, and especially the introduction of stronger lighter materials have helped airship design through lighter gondolas, nose cones, battens and tail fins. These consequences, however, are a spin-off from material developments aimed at conventional airframe rather than as airship specific developments.

However, it is major developments in textile engineering that have been uniquely responsible for advances in airship design, and for this reason this chapter will consider those developments only.

The advances in other structural materials have been adequately covered in other publications.

Material development is a continuing process and no publication can hope to be more than a statement of the current state of the art. This chapter will attempt to look at the progress made in developing textile materials up to the current situation, and give some insight into the properties of textiles that are important in the designing and building of modern airship envelopes.

DESIRABLE PROPERTIES FOR AIRSHIP TEXTILE MATERIALS

Materials ideal for use in pressurised non-rigid airship envelopes would have the following properties:

Envelope Materials

- High strength. The strength of the material will determine the maximum possible size of the envelope.
- High strength to weight ratio to minimise the weight of the envelope.
- Resistance to environmental degradation through temperature, humidity and ultraviolet light. These factors will determine the life of the envelope and its maintenance requirements.
- High tear resistance to give damage tolerance.
- Low permeability to minimise helium loss. Helium loss results in loss of operational capability and increased operational costs.
- Joining techniques that produce strong and reliable joints, not subject to creep rupture.
- Low creep to ensure that the envelope shape is maintained throughout its life.

Ballonet Materials

- Low permeability to both air and helium to minimise helium contamination or loss.
- Good flexure and abrasion resistance with no increase in permeability.
- Low weight.

DEVELOPMENT OF TEXTILES FOR AIRSHIP USE

With the development of synthetic materials, the textiles used in airship manufacture have undergone many changes. The development of these materials from those made of natural fibres through to today's totally synthetic materials is outlined below.

Envelope Materials from Natural fibres

The early envelope materials were exclusively plied rubber coated fabrics, two or three plies of cotton fabric having been bonded together using natural rubber. The cotton plies were biased relative to each other in order, it was claimed, to improve shear strength and stiffness and tear resistance. The natural rubber sealed the fabric although permeability was controlled to a limited extent by altering the amount of rubber in the inter-ply layers, a 'gastight' fabric having more rubber and being heavier than an 'airtight' fabric. To reduce permeability further, the envelope was 'sealed' with paraffin on the inner surface and both inner and outer surfaces of the ballonet.

The envelope material was joined by a mix of sewn and bonded joints although the sewing was primarily to maintain good contact in the joint while the bonding agent, rubber cement, cured. However, under the influence of solar radiation, temperatures sufficient to soften the rubber cement were encountered and the rows of stitching were necessary to prevent joins from slipping apart, until cooler conditions prevailed and the rubber cement rehardened.

The material had poor properties by modern standards. Houmard (1986) refers to a $650g/m^2$ (19 oz/sq yd), three ply cotton fabric having a strength of about 0.7 kN/50mm (80 lb/inch). Because its susceptibility to weathering resulted in a rapid deterioration in strength, not only was it necessary to use large safety factors but the envelope had a short life. Consequently the limited strength of natural fibre fabrics limited the size of non-rigid envelopes to somewhere about $8{,}500m^3$ (0.3 million ft^3).

Introduction of Synthetic Material

The replacement of natural rubber coatings by neoprene (chloroprene) rubbers was the first use of synthetic products in envelope materials. Although neoprene has a higher specific gravity than natural rubber, it has much improved weatherability and a lower permeability to gases. The envelope materials would be expected to require somewhat less maintenance and have a longer life, but the material still had a very limited strength.

However, the introduction of base fabrics made from synthetic fibres gave large increases in strength for less weight. Polyamides (nylon) and polyesters (particularly Du Pont's Dacron) were two very early synthetics that were produced as filament yarns from which fabrics could be woven. The comparison with cotton is shown in Table 6.1 below:

Table 6.1. *Properties of three fabrics*

	Cotton	**Nylon**	**Polyester**
Specific Gravity	1.5	1.14	1.39
Tensile Strength GPa (lb/sq. in)	0.4-0.55 (60-80,000)	0.8 (120,000)	1.0 (140,000)
Tensile Modulus GPa (lb/sq. in)	-	5 (720,000)	12 (1,700,000)

The potential for stronger, lighter materials is evident. The greater tensile modulus of the polyester coupled with its better resistance to hydrolysis (nylon can absorb approx. 4% by weight of water) made it the preferred yarn for the airship envelope materials.

Polyester was the base textile of the lightest envelope fabric used in the Goodyear GZ 20, a 370g/m^2 (10.9 oz/sq. yd), two ply, neoprene coated polyester fabric with a minimum specified breaking strength of 145kN/50mm (165 lb./inch). The largest non-rigid airship ever built, the 42500m^3 (1.5 million ft^3) ZPG 3W, had an envelope constructed from two ply, neoprene coated, polyester fabric with a minimum breaking strength of 2.8kN/50mm (320 lb./inch) in the warp direction at a maximum weight of 560g/m^2 (16.5 oz /sq. yd).

These materials gave much improved strength at lower weights than the natural materials, but still had only moderate weatherability and therefore needed regular envelope maintenance and frequent repainting. The method of making bonded joints was unchanged, and the joints remained prone to degradation.

A further step on this path was the use by Airship Industries, in the Skyship 500 and 600 series of a single ply polyurethane coated fabric. The base fabric, as before, was a plain polyester 550 dtex, 15 x 15 weave spread-coated on both sides with a polyether grade polyurethane and with a layer of PVDC Copolymer (Du Pont's Saran) bonded to one (inner) surface to reduce helium permeability. The material gave a breaking strength of 1.85 kN/50 mm (210 lb/in) for a weight of 370-400 g/m^2 (10.9-11.8 oz per sq yd).

The polyurethane coating gave better weatherability and therefore reduced the need for envelope maintenance with less frequent painting required although this was only true of temperate climates as in the hotter, humid tropics, the degradation suffered by the polyurethane is accelerated.

The method of making the joints was modified in these materials. Instead of an overlapped bonded and sewn joint, the material was butt joined with the load carried by butt straps, strips of envelope material bonded across the join on both the inner and outer surfaces. No joints were sewn. The straps on each surface were of different widths so that the change in stiffness across the joint was gradual and did not induce stress concentrations. The polyurethane adhesives were very effective in carrying the load in shear such that in strength tests, it was usual for the material to fail rather than the joint pull apart. The adhesive maintained its strength to higher temperatures also, loss of strength being seen only at temperatures in excess of 75°C. Additionally, the bonded joints did demonstrate a much better resistance to environmental degradation.

One other feature of this material is that it has allowed the construction of the envelope to be changed. Previously each gore from which an envelope was constructed had been made from a large number of lengths joined at their edges, giving a large number of joins perpendicular to the axis of the gore. The reason is said to be that the material was stronger along the roll length than across the roll width (the terms warp and weft not being applicable to two or more ply materials) so that the stronger direction was oriented in the more highly stressed circumferential direction of the envelope. The material for the Skyship 500 and 600 envelopes, being a single ply, had essentially the same strength in the warp and weft directions but with a greater extension in the warp. Cutting the gore from the length of the roll gave several benefits: the greater extension along the warp was believed to help relieve stress concentrations introduced during the manufacturing process; the reduction in the number of joints required to manufacture the envelope reduced the manufacturing time, reduced the length of join and thus the risk of poorly bonded joins and reduced the envelope weight.

Laminate Materials

The most modern materials which have been developed as envelope materials have been laminate materials. The feature of laminates is that overall properties of the laminate can be tailored by the judicious selection of appropriate components of the laminate. Thus the laminate will consist of components for load bearing, gas retention and to protect against weathering and the environment, bonded together with an adhesive that allows for ease both of laminate manufacture and of joining the material. A typical laminate is shown in Figure 6.1.

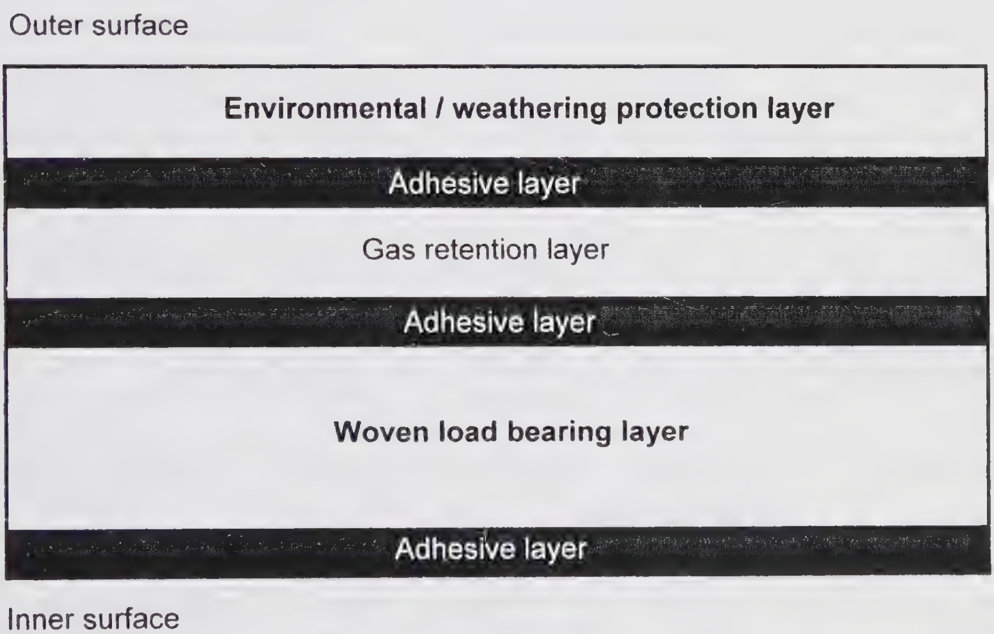

Figure 6.1. Section through typical laminate material.

The structure has an obvious inner and outer face, with the gas retention component sandwiched between the load bearing and weather resistant components. This allows for joints to be made by bonding directly to the load bearing component.

Load Bearing Component

The requirement for an envelope material to be flexible mandates that the load bearing component will be a woven fabric. A large selection of synthetic fibres are now available of which a number of potential suitable candidates are given in Table 6.2 together with relevant properties.

The largest non-rigid airship ever built, the 42500m^3 (1.5 million ft^3) ZPG-3W, had an envelope whose load bearing component was two plies of a polyester fabric. Thirty-five years on, polyester still remains the preferred fabric because, on balance, it has a good combination of required properties, high strength and good dimensional and hydrolytic stabilities. When fabricated, typically, from a low twist 1000-denier yarn, a 13 x 13 count with low crimp and a balanced weave, the cloth has minimum elongation, low crimp interchange, and a high tear resistance. Polyester also has the benefit of a long provenance.

The competing fibres, while having excellent properties in many respects, do not currently achieve such a desirable combination of properties and in some instances have a significant drawback. This may change as greater experience of the newer fibres is gained and their less desirable properties, in this context, are improved or can be compensated for by some other means.

Polyamides have a very similar specific strength to polyester but have greater extensibility and failure strain with a lower modulus; they are also subject to hydrolytic degradation. A polyamide envelope would have poorer dimensional stability with probably a shorter life.

Aramids have a much higher specific strength, a greater modulus and a much lower failure strain, being originally developed as a cheaper alternative to carbon fibres as reinforcement for resins. Superficially they could significantly reduce the weight of an envelope taking only strength into account, and their only apparent major disadvantage is that they are subject to actinic degradation. However, even the lower modulus version of aramid produces a stiff fabric with low failure strain.

Table 6.2: *Typical fibre properties of potential load bearing components of laminate materials*

Material	Fibre Specific Gravity	Fibre Tensile Strength GPa (lb/in^2)	Fibre Modulus GPa (lb/in^2)	Strain to Failure %	WSWF* g/m^2
Polyester e.g. Terylene, Dacron	1.39	1.0 (1.4 x 10^5)	12 (17 x 10^5)	10 - 15	330
Polyamide e.g. Nylon	1.14	0.8 (1.2 x 10^5)	5 (0.7 x 10^5)	20 - 25	350
Aramid - high modulus e.g. Kevlar 49	1.45	2.7 (3.9 x 10^5)	130 (18.8 x 10^6)	2	120
Aramid - low modulus e.g. Kevlar 29	1.44	2.7 (3.9 x 10^5)	60 (8.7 x 10^6)	4	120

It appears that an aramid laminate (or coated material) is not able to disperse stress concentrations which are inevitably introduced during the manufacture of a large structure such as an envelope. The unrelieved stress concentrations can then initiate catastrophic tear propagation. Only when this problem has been overcome or eliminated is there a prospect of stronger and lighter aramid envelopes.

The fibres made from high performance polyethylene (e.g. Spectra and Dyneema) are very different from the material familiar as polythene. In polythene, the long polymer chains are curled up which allows the material to stretch several hundred percent before failure. In the new fibres, the long chains have been straightened and lie along the fibre length, giving much greater strength with much lower failure strain. They are, however, too new to have built up any long term experience of their use although they have the potential to produce the lightest fabrics for a given strength, much less than half the weight of polyesters or polyamides. With similar strain to failure and modulus as aramids, they may be expected to suffer from the same inability to relieve induced stress concentrations, which could initiate catastrophic tear propagation.

Polyimides (Nomex) are known for their exceptional fire resistant properties (not a property normally specified for a helium filled envelope) but in other respects demonstrate similar properties to polyesters, but at a higher cost.

Fabrics made from woven glass fibres are used extensively in the air supported building and tensile structures field, usually coated rather than laminated. They produce very stiff fabrics which require careful handling as they are prone to damage when creased. It is not believed that they will produce a viable envelope fabric.

Gas Retention Component

The gas retention component can come as either a coating or a film. All the early materials used coatings as the gas barrier, as do materials now used for ballonets, although with the modern laminates, a film is incorporated as the gas barrier. The properties of materials that have been, or could be used as the gas retention component are given in Tables 6.3 and 6.4 for coatings and films respectively.

Just as the other components can contribute to minimising helium loss, the gas retention component has more than a single function. In addition to low permeability, it must possess shear stiffness to be able to enhance the overall stiffness of the laminate, and be able to be securely bonded to both the other components (being sandwiched between them). Poor adherence to either could result in delamination.

In practical terms, polyester again is the preferred material, with polyester film (Mylar - Du Pont) being the most common component. Polyester film has low permeability and is relatively strong and stiff.

Table 6.3a: *Typical properties of coatings potentially suitable for envelope materials*

Material	Specific Gravity	Hardness (Shore A)	Tensile Strength	Abrasion Resistance
Natural Rubber	0.93	30-100	(3,000)	Excellent
Neoprene	1.23	40-95	(3,000)	Excellent
Butyl	0.92	30-100	(2,000)	Good
Silicone	1.1-1.16	25-80	(1,000)	Poor
Chlorosulphonated P.E (Hypalon)	1.12-1.28	50-95	(3,000)	Excellent
Polyester Elastomer (Hytrel)	1.17-1.25	40D-72D	3,600-5,500	Excellent
Polyurethane	1.05-1.30	35-100	(4,000)	Excellent
PVC	1.20-1.35	40-90	(1,500-3,500)	Excellent

Table 6.3b: *Typical properties of coatings potentially suitable for envelope materials*

Material	Permeability	Heat Sealable	Weatherability	Adhesion to Fabrics
Natural Rubber	Fair	No	Poor	Excellent
Neoprene	Low	No	Good	Excellent
Butyl	Very Low	No	Excellent	Good
Silicone	Fair	No	Excellent	Good
Chlorosulphonated P.E (Hypalon)	Low	No	Excellent	Good
Polyester Elastomer (Hytrel)	High - Fair	Yes	Good (with additives)	Good
Polyurethane	Low	Yes	Good	Excellent
PVC	Fair - Low	Yes	Good	Excellent

Table 6.4a: *Typical properties of film materials for possible use in laminated materials*

Material	Tensile Strength	Ultimate Elongation	Gas Permeability	Adhesion to Fabrics/Film
Polyurethane	4,000-10,000	400-600	Low	Excellent
Polyvinyl Fluoride	8,000-16,000	90-250	Low	Poor
Polyester	25,000-45,000	40-120	Low	Fair
Nylon	10,000-17,000	300-500	Very Low	Fair
PVDC Copolymer (Saran)	7,000-16,000	30-60	Very Low	Fair
PTFE	3,000	300	Fair	Poor
Low Density Polyethylene	1,000-2,300	90-800	Fair	Poor
PVC	1,000-3,000	200-400	Fair - Low	Excellent

Table 6.4b: *Typical properties of film materials for possible use in laminated materials*

Material	Heat Sealable	Weatherability	Flex Fatigue Resistance	Dimensional Stability
Polyurethane	Yes	Good	Good	Poor
Polyvinyl Fluoride	Yes (with adhesives)	Excellent	Excellent	Good
Polyester	No	Fair	Fair	Excellent
Nylon		Poor	Excellent	Excellent
PVDC Copolymer (Saran)	Yes	Poor	Fair	Good
PTFE	Yes (some grades only)	Excellent	Good	Good
Low Density Polyethylene	Yes	Good if pigmented	Excellent	Poor
PVC	Yes	Good	Good	Poor

Weathering Component

Some of the materials that have been considered as a gas retention component are also an effective weathering component, but one material stands out from the others, having been used for many years as a protective film. Polyvinylfluoride (PVF) film, commonly known by its trademark, Tedlar (Du Pont) has proven to be virtually inert at ambient temperatures to a wide range of acids, alkalis and solvents and has far greater resistance to actinic degradation than most synthetic materials

A comparison of fabrics with laminated PVF film against coatings used previously is shown below.

<u>Neoprene</u>

- SG 50% greater than polyurethane or PVF.
- Modest weatherability gives 3 year life with frequent maintenance i.e. painting.
- Must be joined with adhesive.

<u>Polyurethane:</u>

- Very low helium permeability.
- Very good handling properties and crease resistance.
- Good weatherability gives 5 year life with modest maintenance.
- Very easy to handle and join (by adhesives or heat bonding).

<u>Polyvinylfluoride</u>

- Very low helium permeability.
- Resists fungal growth.
- Excellent weatherability gives 15 to 20 year life with no maintenance.

The very large increase in predicted envelope life shows the superiority of PVF laminated materials, especially with the zero or minimum maintenance. This extended life coupled with the minimum maintenance greatly offsets the increased material and envelope manufacturing costs and a rigorous analysis would be expected to show a much reduced life cycle cost for an envelope.

Bonding and Joining

The bonding agent that holds the laminate together is also the agent responsible for making joints and is thus a very important component of the laminate. A meltable bonding agent is specified both to aid in the manufacture of the material, and to improve the reliability of the joints. No methods exist to inspect joins, whether heat sealed or adhesively bonded, but the greater control in making heat sealed joints over adhesive bonded joints improves the reliability of the heat bonded joint.

The choice of material with these capabilities is very limited. One material that has been successfully used is a polyester elastomer manufactured by Du Pont under the trade name 'Hytrel'. This material has the properties required as a bonding agent, and also makes a contribution to the low permeability of the laminate.

The nature of these bonding agents requires that aggressive solvents are used during the manufacture of the laminate. This has caused some problems in the past as certain of the solvents used have been banned by Health and Safety Regulatory bodies, necessitating the sourcing of usually more expensive replacements.

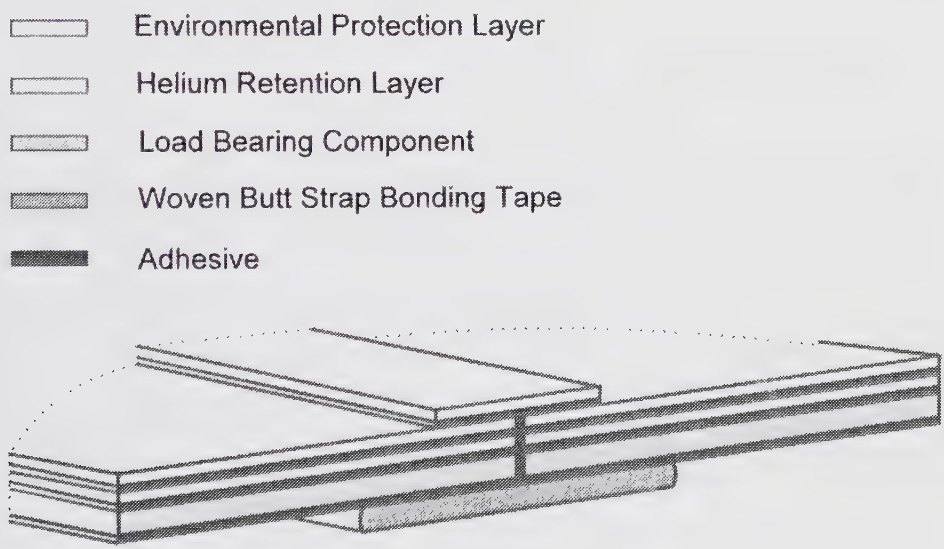

Figure 6.2. Section through typical laminate material joint.

A typical laminate joint is shown in Figure 6.2. The material is butt joined with a specially made tape as the butt strap, the joint being heated and cooled under pressure. This strap carries all the load across the joint, while the outer strip of weather resistant material is bonded there purely to seal the joint against the environment. The tape used as the buttstrap is specially woven to have high strength across its width and is impregnated with the bonding agent. Similarly other special tapes in the form of 'T's or 'X's, also impregnated, are used for making special joints or attachments to the envelope.

As with the polyurethane coated materials, the joints in the laminated materials are stronger than the materials themselves. In testing, the normal failure is found to be in the material, not in the joint.

Potential of Laminate Materials

The laminated fabrics have the potential to produce very high strengths at low weight. For the US Navy YEZ 2A design which has a nominal envelope volume of 70,800 m^3 (2.5 million ft^3), a single ply Dacron, laminated with Mylar and Tedlar using Hytrel as the bonding agent, was developed which gave a uniaxial strength of 5.25kN/50mm (600lbs/in) at a weight of 440 g/m^2 (13 oz per sq. yd). Derivatives of this fabric are under development which have the potential to achieve a uniaxial strength of 14kN/50mm (1600 lb./in) at approximately 1 kg/m^2 (30 oz per sq. yd).

It is believed that a non-rigid airship with an envelope of 1.1 million m^3 (40 million ft^3) is feasible with a material of this strength (Munk).

Ballonet Materials

The preceding sections have considered envelope materials, *i.e.* the hull materials. The ballonet, however, is an important component of the envelope and the material from which it is fabricated requires an unusual combination of properties. The ballonet is continually inflated and deflated, moves against the inside of the envelope and itself, and during flight manoeuvres is subject to 'ballonet slosh', which can induce loads into the material, although since there is no pressure differential between the ballonet air and envelope gas, there is no pressure induced membrane stress in the ballonet material.

Ballonet materials therefore are required to be able to resist continual flexing and abrasion without increase in permeability, and to have moderate strength. Both coated and laminated materials have and are still being used.

The coated material is a lightweight nylon or polyester scrim coated on both sides with polyurethane; in some materials the coating is spread coated on one side and film transfer coated on the other. The combination of coating material, coating process and open weave scrim gives a very supple material with good flex properties that are maintained during extensive flex testing. The soft surface that goes with the suppleness would be expected to have greater friction when rubbing against itself or the envelope, but in practice, must have sufficient abrasion resistance as abrasion problems have not been reported.

The laminate materials have an additional thin 0.01mm (0.25 mil) film of polyester bonded to the polyurethane coated, closely woven fabric. The combination of close weave and the film give a much stiffer fabric but with lower friction characteristics on the polyester laminated surface. Manufacture of the material itself is more difficult, and joining is also not as easy as the polyurethane coated materials. While the flex properties are not as good as the coated materials, as would be expected from the greater material stiffness, the laminated materials form perfectly serviceable ballonets with no reported service failures. The inference must be that the flex test used, while showing differences in material flex properties, does not sufficiently represent the flex conditions experienced by a ballonet in service.

The materials are assumed to require only moderate strength since they are not subject to a continuous membrane load resulting from a pressure differential across the ballonet material. The ballonet, however, is subject to 'slosh' where the ballonet is observed to move violently under certain flight manoeuvres and significant loads in the ballonet material could be encountered. To my knowledge, no measurements of these loads have been made.

PROPERTIES OF ENVELOPE MATERIALS

The design of an airship envelope is affected directly or indirectly by a large number of material properties, and very often compromises will need to be made over conflicting issues. In this section, the background to a number of the more important properties is considered.

The preceding sections, however, have shown that the coated or laminated envelope materials are, in reality, complex manufactured structures. In conventional engineering structures, we can relate the behaviour of the manufactured structure, for instance a roofing truss, to the properties of the materials of which it is made, and its behaviour is critically dependent on its design. The behaviour of laminated envelope materials usually cannot be directly related back to the properties of their component parts, and we ascribe the term 'property' to describe the macroscopic behaviour of the complex manufactured structure. Not surprisingly, small changes in the manufacture or structure can have significant effects on these 'properties'.

In general, specific figures of the material properties discussed in the following section have not been given since they could be atypical and in the worst cases, misleading. It should also be remembered that in addition to the work openly reported, many of the values are unreported as they are considered to be commercially sensitive by both the manufacturers and users.

Stress - Strain Properties

The uniaxial tensile strength, is probably the property most often quoted for an envelope material, and while a very important parameter, it gives limited information about the anisotropic non-linear stress - strain properties of broadloom fabrics, whether coated or laminated. Further, modern stress modelling techniques capable of catering for non-linear materials require detailed data on stress - strain characteristics of the materials over the complete range, including bi-axial loading conditions.

Biaxial Loading

The testing of woven fabrics under biaxial stress conditions has never been an easy test to carry out and biaxial testing is not a common standardised test. In recent years, however, the methods have progressed and several test machines, capable of producing a biaxial stress field by superimposing two orthogonal stress fields, have been described with the detailed test procedures required (Reichardt, Woo and Montgomery, 1953; Niwa, Kawabata and Kawai, 1971; Reinhardt, 1976). The test machines are complex instruments; one such that gave repeatable results was described thus, "...having a rigid frame 3m x 3m and ten hydraulic pistons on each side which are transversely movable and independently adjustable so that inaccuracies in the specimen can be equalised. The specimen has a square field of 50 cm x 50 cm...." (Losch, 1971).

Measurements of biaxial stress - strain behaviour using this type of equipment have been carried out to validate theoretical predictions of behaviour based on simplified models of the fabric structure and properties of the fibres (Kawabata *et al.*, 1973) or to validate finite element models of cruciform test specimens under biaxial loading against practical measurements (Minami and Nakahara, 1981).

The generation of biaxial stress - strain data is a time consuming task since it has been normal practice to measure stress - strain characteristics in one direction while the orthogonal direction is maintained at constant load (or strain) To gather data over the full range of biaxial stress conditions requires a large number of repetitive tests.

A cautionary note must be made: it has been my experience that in carrying out biaxial testing on nylon fabrics, the hysteresis effects are very significant and reproducible results could be obtained only if the test sample was allowed to recover for 24 hours after undergoing a single test cycle (Render and Bradley, 1986). If this is also the case for coated or laminated materials, the generation of full range biaxial test data could be lengthy and costly, although simplifying methods of predicting biaxial stress-strain properties from limited data have been shown to be effective (Kageyama *et al.*, 1988).

Shear Properties

Any envelope will be subject to significant shear loads, and any stress modelling technique will require shear strain data. As there is a need for reliable biaxial stress-strain data, similarly there is a need for reliable shear strain data.

There are models of shear deformation of woven fabrics (Kawabata, 1989) and even of "fibrous assemblies" (Pan and Carnaby, 1989) such as non woven fabrics, based on the bending, rotation or slippage of crossed fibres or yarns. For uncoated cotton fabrics, a close correlation between measured and predicted shear deformation properties has been found, the measurement method being based on an adaptation of a complex biaxial test machine (Kawabata, 1989).

The coating of a fabric, however, or bonding the fabric to a film, as in the laminate materials, drastically changes the shear behaviour, significantly increasing the shear strength and stiffness. Measurements of shear properties have been made, usually based on inflated cylinders. In one study (Alley and Faison, 1972), a pressurised cylinder made of polyurethane coated nylon fabric could be independently, axially and torsionally loaded so that the circumferential, longitudinal and shear stresses could be independently varied, with deformations being recorded by photographing a grid drawn on the cylindrical surface. These measurements were claimed to be valid for increasing load only, since for cyclic loading the stress - strain characteristics were found to be explicitly dependent on the preceding load history.

The measurements on coated fabric described above are not new and it would appear that little has been published recently. In general, however, if particular shear data are required by the designer or stress analyst, methods do exist whereby this may be obtained.

Permeability

Envelope materials do not form membranes impervious to gases. Not only will helium diffuse from the envelope, but, in theory at least, atmospheric gases and water vapour will diffuse into the envelope since diffusion of a gas through a membrane is dependent on the difference in partial pressures of the gas on either side of the membrane. Helium is a monatomic gas and has the smallest molecular diameter of all gases with a consequence that, under identical conditions, it will diffuse through a material more rapidly than any other gas. In contrast, the atmospheric gases, mainly oxygen and nitrogen, have much greater molecular diameters, and any diffusion into an envelope is assumed to be very small - an assumption that operating experience validates. As a comparison, the permeability of nitrogen through PVF is approximately 0.05% of that of helium so that helium loss would outstrip any dilution effect by a large margin.

The loss of helium from an envelope is a major consideration from an operational viewpoint. It cannot be prevented since helium will diffuse through any envelope material - even as it must have done through the aluminium alloy skin of the metal clad US Navy airship ZMC-2.

Helium loss has two effects:

a) it leads to loss of lift and hence a reduction in operational capability of the airship; this is rarely a safety issue since the loss is normally at a known rate and can be accommodated.

b) it adds to the operational costs since to maintain the operational capability, the helium must be replaced.

While as envelope size increases, the square/cube laws ensure that helium permeability has a diminishing effect on operations, (the helium loss reduces as a fraction of the total helium fill), in financial terms, the larger the envelope the greater is the volume of helium lost for a given permeability. The need to minimise helium loss has always been present, but the approach has changed from increasing the weight of rubber or coating the envelope with paraffin to choosing materials with the least permeability to helium.

Because the measurement of helium permeability, using standard methods, was found to be variable and the measurements did not correlate with the achieved daily lift loss TCOM instigated a study into the measurement of helium permeability in their laminated envelope materials (Ashford *et al.*, 1983). The permeability of these laminated materials (or more strictly permeation, since the term 'permeability' is applied to single materials while 'permeation' is applied to composite materials) was measured by independent test laboratories with large variations in the results obtained from nominally the same test apparatus and methods. By careful attention to experimental detail and methodology, they succeeded in developing a reliable and repeatable test method.

From the permeability of the laminate components, as supplied by the material manufacturers, it was possible to calculate a theoretical value for the permeation of the trilaminate i.e. the Tedlar and Mylar laminated to Dacron with Hytrel as the bonding agent. This value was found to be 1.14 l/m^2DA (litres/[square metre][day][atmosphere]). and compared well with the measured value of 0.99 l/m^2DA.

Of more practical interest, they calculated the theoretical lift loss of a 411,000 cu ft aerostat, based on the measured permeation value, to be 12 lb. per day against the lift losses of 14 to 16 lb. per day measured from several aerostats. This would lead to the conclusion that helium losses, often believed to be the result of leakage through hardware or pinholes, is, in the new generation of envelope materials, almost entirely due to permeation of helium through the envelope material.

Further reductions in permeation can be achieved only through the selection of an improved gas barrier film and since it is possible to predict the permeation from the component materials permeability, the search for a better gas barrier film can be concentrated on those with known low permeability.

Tear Resistance

The new generation of envelope materials are tougher than those used previously, but this is difficult to quantify as the methods of measuring tear resistance that lead to a quantitative prediction of envelope tear behaviour are not fully developed and to my knowledge none of the data on laminate materials that has been published relates to catastrophic tear propagation - amongst the most critical features of an envelope material. The background to tear measurement gives an idea of the difficulty in obtaining adequate data.

Measurement of Tear Strength

Methods of measuring tear strength and resistance have been developed over many years. Harrison (1960) published a comprehensive literature survey into the tearing strength of textile materials, containing over 200 references spanning the years 1910-1960.

Quantitative measurements of the tear strength of textile materials go back to the early decades of this century, not surprisingly when it is considered how important textile materials were in the manufacture of aircraft. Tearing was considered a major failure mode in textile materials both from direct tearing resulting from snagging and for propagation of a tear from damaged or holed areas e.g. a bullet hole in the fabric covering of a wing.

In addition to aircraft fabrics, tearing strength was cited as important in fabrics used for parachutes, tentage, wagon covers and even industrial fabrics used for bags and sacking.

A large effort was therefore put into methods of measuring tear strength and many of the methods still used to this day were developed during World War I. The wounded (slit) tensile test, single rip and tongue tear tests, trapezoidal test and wounded (slit) burst test were developed and several are used to this day. All of these tests, while effective in giving comparative tear strengths of textiles, do not give results that can predict how a tear in a textile will behave in a given situation, although some attempts were made to define conditions under which tear propagation would occur.

The tests did allow qualitative effects to be outlined, all the analyses being based on the assumptions that:

- in tearing, all threads are broken singly and tear strength is roughly proportional to the single thread strength of the threads broken;
- although broken singly, several threads adjacent to the next thread about to break, are put under tension by the tearing force;
- the number of threads tensioned this way is determined by the thread spacing.

Based on these assumptions, qualitative statements about the effect of different fabric features were made, generally based on how these features affected the load carried by the adjacent threads ahead of a tear. These are summarised below:

- Yarn smoothness (or roughness) through the friction between crossed threads, and extensibility affect the loads that can be carried by threads adjacent to the next one due to break (i.e. load concentration ahead of the tear).
- Yarn twist has a secondary effect through changing yarn smoothness and thread spacing.
- Increased thread strength through use of a coarser yarn affects tear strength, but while even a small increase in coarseness could substantially increase the rip strength, a considerable increase in coarseness is necessary to increase the wounded tensile strength.
- The effect of thread spacing, being inconsistent and depending on other features, is secondary.

- Crimp has two effects: a higher crimp gives a more extensible fabric, and thus a wider distribution of load ahead of a tear and higher tear strength; but a reduction in ease of slippage because of the greater bend in higher crimped threads leads to a lower tear strength. In the wounded burst test, ensuring that warp and weft (fill) extensibilities are equal, by controlling the crimp balance, burst pressures are improved.

- Weave affects the sleaziness of the fabric, the ease of thread slippage and the number of threads breaking together, and the superiority of matt-weaves over plain-weaves was shown.

- Finishing processes such as scouring, bleaching or dyeing affected the tear strength either by altering the thread strength or altering the thread smoothness and thus effects were secondary. Processes, however, such as mercerisation and the use of water repellent waxes affected 'yarn lubricity', thus promoting thread slippage and distribution of loads.

- Coatings, all lumped together as having a similar effect, were shown to reduce the tearing strength by an amount dependent on the restriction of thread movement.

Harrison's survey is a very comprehensive summary of the state of knowledge current in 1960. The bulk of work surveyed concentrated on the rip and trapezoidal tear tests using uncoated fabrics. In these tests, the load applied directly to the tear to cause it to propagate was measured, while the fabric away from the tear is unstressed. If the load was removed the tear ceased to propagate. Tearing mechanisms proposed in the analysis of tear propagation assumed that threads broke individually, and that threads close to the tear were loaded. Quantitative analysis on this type of tearing closely described the behaviour in terms of basic fabric and yarn properties.

In both wounded tensile and wounded burst tests, however, a different type of behaviour was observed. The test samples were evenly stressed under increasing load, and at some load the wound began slowly to propagate. At this stage, if the load was removed, propagation ceased. At some slightly higher load, however, tear propagation became catastrophic, the tear propagating at some hundreds of feet per second. While it was believed that the same principles applied to this behaviour as to conventional tearing, no theoretical analysis of rapid tear propagation had been carried out.

It is possible that this mode of behaviour was not perceived to be of major importance; according to Abbott and Skelton (1972), catastrophic propagation is more likely to be seen in coated fabrics, a topic scarcely touched by Harrison's survey. Accordingly, none of the effort carried out before 1960 can help in determining the susceptibility of large stressed fabric membranes to the catastrophic extension of an existing tear.

While new approaches to failure have been developed that can be applied to tear propagation in textiles (and textile based materials), the general concept of tear behaviour is still heavily influenced by the approach described by Harrison.

Fracture mechanics approach

The recognition that all materials and engineering structures contain flaws or defects, that under certain conditions can propagate catastrophically, has lead to the development of fracture mechanics. Initially developed to explain the behaviour of brittle, high strength materials, its application has been extended to the behaviour of ductile materials.

The fundamental of fracture mechanics is the definition of a function known as the stress intensity factor. This function describes the stress field concentration around the tip of a crack (or end of a tear) in terms of the overall stress and crack length.

The function, when conditions are linear elastic, takes the form:

$$\sigma_f = K / (2a)0.5 \qquad (6.1)$$

where

σ_f = applied stress
K = stress intensity factor
a = crack semi-length

Below a certain value of the stress intensity factor, the crack will not propagate or propagate only slowly. Above this value of the factor, crack propagation is catastrophic. This critical value, K_c, has been shown to be a material constant and can be considered to be a measure of material toughness.

The fracture mechanics approach recognises different forms of crack opening: Type I is tensile opening of the crack in response to tensile load across the crack in the plane of the material; Type II is a shear opening of the crack in response to a shear stress along the crack, in the plane of the material; Type III is a shear opening of the crack in response to a shear stress across the crack, normal to the plane of the material.

Until the advent of fracture mechanics approach, most of the investigations into the tear resistance of textiles have been carried out using some form of tear test where the tear opening is of Type III and national specifications for these types of test are still current. In contrast, the type of failure seen in stressed textile structures is Type I tear opening where at some point the tear extension becomes uncontrollable. Considering this difference in mode, it is not surprising that conventional tear testing has given no information on the response of an envelope to a tear. Conventional tear testing may have its uses as a quality acceptance or monitoring test, but even this is debatable since tear strength correlates well with single thread strength and any changes would be reflected in the textile tensile strength.

Application of Fracture Mechanics Approach to Textiles

During the 1970s and 1980s the principles of fracture mechanics have been applied to coated textile materials. The impetus for this work has been primarily driven by the use of high strength coated textile materials in two areas: air supported structures (air houses) and tensile structures for large span roofing. In both these types of structure, uncontrolled propagation of a tear initiated at a flaw could have disastrous results and since the materials used are susceptible to foreign object damage e.g. objects blown by high winds, it is probable that the stressed materials will sustain damage at some time (Ansell *et al.*, 1984).

As in an airship envelope, the initiation of the tear is far less important than its propagation characteristics. A growing body of literature exists which addresses the problem of tear propagation. Findings are summarised here but the reader is advised to consult the original papers for more details

Earlier attempts were made to measure tear propagation (Kawabata, 1989) or critical tear lengths in pressurised fabric cylinders (Topping, 1973) and provide theoretical assessments. These studies recognised shear stiffness of the material as an important factor, since it is through shear that the stress concentration at the tear tip is diffused away.

There have been attempts to derive a theory for tear propagation in coated fabrics based on the propagation of a tear in a uniaxially or biaxially loaded test specimens (Minami, 1978; Williams and Gaafar, 1984), and to correlate test results with theory (Minami, 1978).

Minami (1978) developed a theory based on Hedgepeth's model of stress concentration factors due to cracks in fibre reinforced composite materials (Hedgepeth, 1961) using a form of Griffith energy balance as a criterion of failure. From this unlikely beginning, the function he developed as a measure of toughness is essentially constant for varying crack lengths, a necessary condition for a measure of material toughness.

One aspect of these theories, however, is that they all assume that the stress - strain characteristics of the coated fabrics are linear elastic, while as has been pointed out, the materials are anisotropic and non-linear. I am not yet aware of any developed theories that have taken the non-linearity into account, although it has been pointed out (Racah, 1984) that in the general equation given above, the exponent of a is equal to 0.5 only under linear-elastic conditions.

Both theoretical analyses and practical studies indicate the importance of the stress concentration at the tear tip and the way that the stress concentration is distributed ahead to the tear (c.f. the plastic zone ahead of a crack in a ductile metal). The stress is carried by shear between adjacent threads and size and distribution of the stressed zone is affected by the shear stiffness or modulus of the material. The greater stiffness of the laminate materials appear to enable the stress concentration to be diffused over a greater distance with a consequently improved tear resistance.

Uniaxial and Biaxial Tear Testing

While most tests have been carried out under uniaxial tension, a growing number have been carried out under biaxial tension. It has been shown that the load at which tear propagation starts is less under uniaxial tension than under biaxial because "since the lateral deformation which is caused in the vicinity of a defect under uniaxial stress is suppressed in the case of biaxial stress, the magnitude of concentrated stress in the vicinity of the defect becomes smaller in the case of the biaxial stress condition" (Minami and Motobayashi, 1981), a finding that has been theoretically predicted (Williams and Gaafar, 1984).

This finding does suggest that tear propagation data obtained from uniaxial testing is sufficient since the results found are pessimistic relative to the more complex and more costly biaxial tear testing.

The standard uniaxial slit tensile tests, however, may give unrepresentative results if the sheared area, which carries the load away from the tear tip, is interfered with by the test machine grips or the edges of the test sample. Small test samples as found in the standard tear strength tests are probably of insufficient size and it has been proposed (Racah, 1984) that for realistic tests, the test sample length should be a minimum of 20 times, and the width 5 times, the initial tear length. The test sample, therefore, is not necessarily a constant size, and large samples, up to 1 metre square, may be required.

The problem of tear propagation in coated and laminated textiles has not yet been solved. Sufficient progress, however, has been made to identify important factors and give confidence that further effort in this topic will provide a practical measure of material toughness.

Flexural Properties

It has been stated previously that ballonet materials must be able to resist continual flexing and abrasion without increase in permeability. While easily stated in general terms, in practice, it is more difficult to define what is required as a test of these properties and to lay down acceptance criteria - what level of a parameter is or is not acceptable. In addition, it is often the permeability that is measured after a sample of material undergoes a fixed flexural regime intended to simulate the flexural conditions expected in practice.

Consequently a variety of tests have been developed specifically for both envelope and ballonet materials that are unused by any other industry, while other industry specific tests have been borrowed.

A relatively early flexural test is the Rotoflex test specified in US military airship material specifications. In this test, a circular specimen is gripped across a diameter at a fixed load, and one grip rotated ± 270° for 200 cycles This is then repeated for other diameters, the new orientation depending on the thread directions. After this treatment, the permeability must not have increased beyond a given limit, nor the strength dropped below a percentage of the untreated strength. This procedure can be seen as an attempt to simulate the flexing undergone by the materials in practice, but is more of a conditioning process carried out before measuring the materials' permeability and strength.

A conditioning procedure aimed primarily at the handling properties of aerostat materials is called Twist-Flex. This simulates a very severe handling regime. Two interlinked cylinders of material, approximately 0.3m diameter by 1.2m long, with a common axis are alternately inflated and deflated. The inflating cylinder twists the deflating cylinder through half a revolution while crushing it from 1.2m to 0.2m in length. The process is then reversed, the air being exhausted from the inflated cylinder and pumped to the deflated cylinder. The normal handling of an aerostat including manufacture and deployment is said to be represented by 100 twist-flex cycles.

A variety of tests, several coming from the leather or shoe industries, have been adapted and used by the airship manufacturer or their material suppliers, with each one having both advantages and disadvantages, and some have been developed into national specifications (ASTM D2097-84, BS 3424:Part 9:1980).

The specific test employed is probably unimportant if the test is being used purely comparatively, or the user has carried out sufficient testing to correlate the test results with resistance to damage by flexing that his application requires.

IMPROVED LAMINATES

A recent potential addition to the range of materials from which envelopes could be fabricated has emerged - laminates which have been developed as sailcloth for high technology racing yachts.

While the basic construction of these laminates is similar to those described earlier, the major difference is that the load bearing component is a scrim. Normally laminated between two polyester films, the scrim is not woven and is made from yarns with neither twist nor crimp. The yarns are laid in the warp and fill directions, and in any required bias direction. By a combination of different weights and different types of yarn, the material can thus be manufactured to give different desired strengths and stiffness' in different directions. The laminates are claimed to be light, stiff and strong, with excellent tear resistance.

While extensive test programmes must have been carried out during the development of these materials, it appears that only very limited information on the laminate properties has been published. Nevertheless, the laminates do appear to have the potential of being developed into ideal envelope materials.

SUMMARY

This chapter has attempted to give some insight into the properties of textile based materials from which an airship envelope can be made.

While major developments in textile engineering and science have transformed the capabilities of these materials, some important properties and characteristics are still poorly understood and their impact on envelope design not fully recognised.

I believe a common mistake is to consider a woven textile material, whether coated or laminated, as an isotropic thin sheet.

It should be remembered that textiles are anisotropic, have non-linear stress-strain properties, and their orthogonal stress-strain properties interact through crimp interchange.

Having said that, they are engineering materials that behave according to fixed rules, even if the rules may occasionally be somewhat obscure or not fully understood.

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7

Structures

C. Luffman

INTRODUCTION

Airship structures traditionally fall into four groups: rigid, non-rigid, semi-rigid and hybrid. Rigid Airships normally have an overall skeletal frame, to hold their form (carrying overall bending), which is covered in light dope-tautened material (to produce an aerodynamically smooth outer profile), into which are fitted separate gas containment cells. All other systems and structural features are carried by the skeletal frame. An exception to this class of airship are those which utilise an outer monocoque shell, stabilised by internal gas pressure (similar to the ZMC-2 metal-clad, built in 1929). This latter type may also be referred to as a pressure airship.

Non-rigids are also pressure airships, since they maintain their form by pressure stabilisation of the gas containment membrane (the envelope) - similar to aerostats. The membrane material is normally a flexible gas-tight and weather-proofed fabric, enabling it to be folded when the envelope is deflated. They are sometimes referred to as blimps. They do not have a skeletal frame, since the envelope under pressure acquires a residual membrane tension, becoming stiff enough to resist overall bending effects and to carry all other structural features without reducing the membrane tension to zero.

Semi-rigid airships combine features from both types, essentially providing a rigid full-length lattice beam (normally a keel structure) and a pressurised envelope, which act together to carry the effects of overall bending and maintain shape. In a keel structure of sufficient proportions, the lattice beam can replace the need for a separate car, providing the housing for the airship's systems and the means to mount the propulsion and landing gear units. It stiffens the lower envelope, which suffers owing to low static head (reducing the stabilising gas pressure longitudinal tension); hence enabling hogging bending loads to be carried and spreading the weight of the installed systems over the envelope's entire length (Pagon, 1927).

These three types of airship are normally of conventional cigar shaped form, designed to minimise drag, enabling them to be directed through the air (i.e., dirigible) via aerodynamic surfaces and propulsion units. Hybrids are non-conventional types of airship, of special form, not necessarily relying on conventional methods for their means of lift, aerodynamic control, propulsive system or structural arrangement. Although general principles may be applicable to hybrid airships these are not specifically covered by this chapter.

HISTORICAL

With advances in material sciences, joining techniques, analytical facilities, design aids, atmospheric awareness and aeronautics in general, there is the opportunity for efficient modern airships to be introduced at competitive prices.
A number of lessons should be noted from the past, namely:

- Atmospheric disturbances must be respected and understood. Some airships have been lost owing to severe weather or turbulence (Althoff, 1990), including those at mooring masts or whilst passing through their hangar doorways.

- Tail surface loads must not be underestimated. The R38 (Kinsey, 1988), may have been lost owing to structural failure for this reason.

- Airships need to be fully tested before entering service. This must not be rushed or side-stepped by those eager to impress or earn revenue before the new type has been properly endorsed by the certifying authorities; this may have been a contributing factor to the R101 disaster (Chamberlain, 1984).

- Rigids tend to be fragile - unforgiving; while non-rigids are more flexible and resilient. For example, if the tail surfaces of a rigid were to strike the ground inadvertently, serious structural damage might follow; whereas a non-rigid's envelope might deflect temporarily without failure - popping back into shape when the load is removed.

GENERAL PRINCIPLES AND CONSIDERATIONS

This section introduces the reader to airship principles and aspects, which must be given structural consideration.

Equilibrium Control

An airship's structure must provide facilities essential to weight control over the effects of buoyancy (gas lift). Whenever appreciable differences occur compensating ballast must be added or dumped to enable the airship to maintain equilibrium. This may occur for several reasons, for example:

- Rain wetting or evaporating from the envelope.

- Gas superheat changes from varying sunlight or other weather changes.

- Fuel usage.

- Embarkation or disembarking.

As the overall capacity for compensating ballast is large to cover these aspects (about 15% of the gas lift), and its position affects balance; it has a major influence on the design of the airframe. Adequate structural provision must be made for the ballast's support, containment, access, fill/dump, quantity measuring and anti-icing arrangements.

The requirement for equilibrium control also affects the way servicing arrangements are executed. Special procedures need to be developed to transfer compensating weight between the airship and the ground as an item (such as an engine) is installed or removed, to enable such service arrangements to be performed. These details need to be sorted out early in the design, since their influence affects the layout of the structure and provision of hard points for lifting.

In addition, for emergency escape purposes, the facilities and procedures must ensure the airship will remain on the ground following a forced landing. This probably requires a controlled but rapid means to dump the lifting gas. As buoyancy is lost, however, support of the airship's weight transfers from its hull to the ground. The airframe must be designed to accommodate the redistribution of load in a way that ensures it settles to a steady position, without tipping over, blocking or affecting the escape positions, and without collapsing on top of personnel.

As weight is transferred, the ability of the landing gear to withstand the resultant loads may be questionable. Since an airship can be fitted with only one support unit, pendulum stability normally keeping the airship upright, release of the lifting gas with such a configuration would also cause the gondola to tip over. The landing gear should, therefore, be designed to collapse gracefully, without puncturing the airframe, and/or be retracted as necessary.

Motions at the Mast

An airship's structure must be designed to accommodate the ceaseless motion arising from atmospheric disturbances when moored. Clearly this significantly affects the design of landing gear, mooring structure, handling features and their carry-through structures. Loads and fatigue criteria must be established to accommodate the effects, the airship's movements probably being uncontrolled. Limitations and procedures must also be established to ensure the airframe is not subjected to the effects of abnormal convective activity. An auto-stabilisation system, which provides auto-pilot control of the airship at the mast, may usefully limit excessive loads from being developed during gales.

An important design case, which the airframe and installed systems must be designed to withstand, is the possibility of a kiting motion where the tail rises up to such an extent that the airship reaches an attitude with its longitudinal axis near vertical - appearing to perform a nose stand. Attitudes up to 70 degrees from the horizontal plane have been recorded, as Figure 7.1 demonstrates.

This may occasionally occur, whilst tethered, due to air turbulence - aggravated by poor location of the mooring site relative to surrounding buildings or regional prominences. The near vertical attitude is probably the critical case for design of the gondola's longitudinal restraint method, since the loads resulting can surpass normal flight conditions. Flight attitudes may be limited to ± 45 degrees. In addition, since the gas pressure varies with height, its container must be designed to withstand the resultant build-up due to pressure head.

Figure 7.1. Airship Industries SKS 600 series airship at a mooring mast.

Unless hangared the airship must be designed to align itself freely with the wind, circulating around its mast (similar to a weather-cock) or rising from the ground in a pitching motion as prevailing conditions dictate. Otherwise the loads of restraint would be impossible for the airframe to bear. If suitable hangar facilities are not available (a rarity for airships at the moment) or weather conditions prevent the airship from being taken in, service arrangements may have to be conducted at the mooring site. As stationary ground equipment or vehicles are a hazard to the moving airship under such conditions, the airship either must be designed to pass safely over necessary obstacles or be restrained (bearing in mind that restraint is only practical during very calm conditions - wind strength less than 5 knots).

Ground related tasks must, therefore, be executed from the airship instead of from the ground. For example, boarding steps must be attached to the airship without touching the ground. As a result, structural access and attachment positions for service equipment needs to be provided on airships that would not be required for heavier-than-air craft. Equipment temporarily installed on an airship may be needed for: boarding, loading, reprovisioning, fuelling, engine changing, and other maintenance actions. Accordingly, the equipment should be designed in concert with the airframe, to ensure the airship's structure is provided with suitable attachments and can accommodate the loading actions.

Boarding facilities must ensure safe personnel transfer, particularly as the airship may move without warning or rise up from the ground owing to atmospheric disturbance. The airframe also should be provided with convenient earth attachment points for use while the airship is held in proximity with the ground, to prevent electrostatic effects - essential whilst fuelling.

Size Effects

The sheer size of an airship's structure has a major influence upon its design. Lengths of members are limited by the capacity of tooling, transport and handling facilities, making additional joints necessary. Major sub-assemblies may need special transport joints to be engineered, so that they can fit into standard containers. Special handling positions also need to be provided to enable lifting equipment to raise them to their installed position.

The overall arrangement of the structure is also affected by the hangar facilities available for its construction and maintenance. Compromises affecting the length to diameter ratio (for a particular lifting gas capacity), tail surface arrangement, propeller installation, landing gear length and gondola depth/support method, may need to be made in order to clear it through the hangar's doors. This must also be taken into account when considering the prototype airship's potential development.

Structural Fragility

While airships are usually larger than other types of aircraft, the airframe's mass per enclosed volume or surface area is much less. For example, one of the four tail surfaces on a 2.5 million cubic foot airship (70 800 m^3) - which would have an area of about 1300 sq ft (121 m^2) and weigh approximately 1750 lb (794 kg), ie: 1.35 lb/ft^2 (6.57 kg/m^2) - may be compared with:

Glider	1.0 lb/ft^2 (4.88 kg/m^2)
Light aircraft	2.4 lb/ft^2 (11.72 kg/m^2)
Boeing 747	20.0 lb/ft^2 (97.65 kg/m^2)

The delicate nature of an airship's structure is therefore an issue which must be given careful consideration, especially for handling, shipping and other working practices.

Minimum gauge for handling may often dictate the nature of the structure. Problems of panel or member stability also must be considered. To overcome such problems the design might adopt the use of braced frame structures with materials of high strength/weight ratio and high bulk content, skinned with light fabric as necessary. Where access is necessary, honeycomb stiffened panels can be used to provide a durable surface.

Damage-tolerant structural design principles should only be applied as far as practical, recognising that for such vast structures it is not possible to make them damage resistant without increasing the weight by an inordinate amount. Fail-safe principles should be applied wherever possible. Vital parts, the failure of which may lead to catastrophic loss of the airship, should be protected against inadvertent damage, be inspectable and have stringent quality control procedures applied.

Load Factors/Aerodynamic Pressure

When in flight an airship is a gentle giant; other aircraft, by comparison, move speedily. As a result load factors and aerodynamic pressure distributions on the airframe are much lower. Maximum in-flight incremental acceleration load factors, owing to worst gusts or manoeuvring, may only be: 0.75g vertical, 0.5g side and 0.5g longitudinal. Even large passenger aeroplanes, such as Boeing 747s, designed to fly sedately are subject to significantly higher load factors. This difference must be carefully understood, since it leads to much lighter scantlings (designed to accommodate handling rather than the loads of flight).

Failure Effects

When an airship has a failure in flight - for example, total loss of power or the flying control system - it can revert to being a free balloon. Other aircraft probably would crash in similar circumstances. As a result, philosophy in design is often different. Airships, for example, can have their engines repaired in flight. This leads to additional access provision (which must be accommodated by the structure) and the relaxation of some standards. Minor structural damage, such as holes in the gas container, might also have temporary repairs applied in flight.

Endurance Effects

Airships have the potential for much greater endurance than other aircraft. They can be designed to remain aloft for a week at a time without refuelling. With in-flight refuelling this can be extended to months before returning to base. This, of course, affects maintenance or inspection periods and consequently reliability goals for the design of the airframe, which may need to be of a higher standard on critical parts compared with heavier-than-air craft. If the airship is being designed to have such long endurance then facilities to enable inspection of the airframe in flight, along with access and essential safety line attachment positions, should be provided.

Gondola Shear Force and Bending Considerations

An airship's gondola can have more or less continuous support along its length. An aeroplane's fuselage, on the other hand, is cantilevered fore and aft of the wing. The different shear force and bending moment diagrams lead to structures that are fundamentally different. An airship's gondola is lighter and can be much more uniform, with fewer stiffeners, since shear flows are smaller. A layout similar to a boat's hull is not unreasonable, although every effort must be made to minimise weight. The nature of the gondola's structure may depend on the altitude the airship is designed to operate at (leading to the need for cabin pressurisation) and whether it is designed to settle on water.

Aerodynamic Drag

Owing to the relatively slow flight speed of an airship, minor protuberances from the skin line have much less effect on performance. Raised head fasteners - which are structurally better than countersunk head fasteners - external skin straps and other such skin line disturbances can be considered for use when they would not be accepted on an aeroplane.

This does not mean to say that external stringers or a corrugated surface would be acceptable, since skin friction drag would rise appreciably with the increased wetted surface area. Handling lines, tail fin bracing wires and external gondola support cables also create a significant performance loss (owing to their great lengths being positioned across the airflow), so should be retracted, aerodynamically shaped, or faired as necessary.

Emergency Escape

Special emergency escape facilities may need to be devised because airships can become airborne again (owing to buoyancy or bad weather conditions) and (depending on the nature of the incident, type of airship and whether the lifting gas escapes or is released) their envelopes or hull may collapse over the passenger and crew compartments. The facilities must enable rapid yet safe escape under such conditions.

For these reasons conventional heavier-than-air craft escape slides (which rely on the aircraft staying put following the incident and without debris obstructing their operation or the passengers evacuation) may not be suitable for airship use. Special lanyards, clipped to a safety harness, that pay out as the escapees jump from the exit positions (slowing their descent rate and being released when safely on the ground) have been considered for some airship proposals as an alternative. Depending on the airship's role, however, the facilities provided must be suitable for the type, skill and number of people evacuating the occupied areas.

It should also be understood that, in such circumstances, if gusting or windy conditions prevail, the airship may be dragged along, turning broadside to wind and perhaps tipping over, until sufficient lifting gas has been lost for the gondola's weight to take effect. Emergency grappling lines may be required to hold the airship into wind as the lifting gas escapes. Sufficient escape positions that will not be rendered unusable, and the means for the escapees to make their way quickly to the exits (and operate them) whilst the gondola is on its side, need to be provided.

For ditching on water, a sea anchor should be designed, which deploys from the bow to hold the airship into wind. The gondola's structure must be designed to withstand the hydrodynamic and hydrostatic pressures experienced as it enters and sinks into the water. The gondola also must be designed with sufficient watertight buoyancy chambers to prevent it from sinking - should the lifting gas be lost - and hold it at an acceptable attitude long enough for escape purposes.

Consideration should also be given to the problems that the rescue services would face under emergency conditions. Provision for means to keep the airship on the ground, make safe access into the occupied compartments and perform normal emergency functions - such as extinguishing fires - must be covered in the airframe's design. A particular feature necessary is provision to release the lifting gas from an accessible position by an operator on the ground. Such provision must be clearly marked and protected from inadvertent use without restricting intended operation. The method must enable rapid release of the lifting gas under controlled conditions. If possible the method should also prevent the envelope from flopping over emergency exits, which otherwise could hamper further rescue actions. Clearly, implements to clear such debris rapidly are necessary and should be readily available for the rescue services' and airship crew's use.

Weight, Mass Distribution and Balance

Weight limitations and overall balance are difficult to achieve, since small tolerance differences over such big structures have a significant effect. For example, if actual fin weights do not match their design estimates overall balance will be affected owing to the fins' extreme aft position. It is also difficult to predict accurately the centre of buoyancy's position. This is because the gas container's shape (which is indeterminate, but idealised as a regular shape or body of revolution) varies according to applied pressures and other loads, its materials of construction and inertia or gravitational effects.

Inevitably, the difficulty of predicting these values accurately may result in a large balancing weight (penalising performance expectations) needing to be added at the nose or tail to bring the airship's centre of gravity within acceptable limits relative to the centre of buoyancy. Consequently the nose and tail structures should be designed to accommodate such counter weights, as necessary. These may be up to 2.5% of the total gas lift.

Alternatively, the gondola and tail support method may be configured to allow movement before fixing their positions. This complication, untried so far, may be difficult to achieve in practice and will add weight for the adjustment facility.

Excess structure weight may easily result if tolerance limits are not kept tight and strictly controlled. The structural designer must also scrutinise strength reserves to minimise the airframe's weight, since this has a much larger penalty on an airship's performance compared with that of heavier-than-air craft. Increasing the power of an airship's engines is not a feasible way to overcome excess weight problems. This can only be achieved by rigorous weight control or, if things really get out of hand, by increasing the size of the gas containers or envelope.

Because an airship's structure is so relatively delicate its mass and large shear force inputs need to be spread over as wide an area as possible. Particularly inputs from the gondola, tail surfaces, bow structure and propulsion units. This prevents excessive deflections and enables an efficient structure to be designed. Inevitably, however, large concentrations of mass are bound to occur; particularly in any attempt to locate the airship's various systems conveniently (for example, everything installed in or from the gondola) and maintain balance. Compromises reached in this area establish the nature of the eventual structure, its layout (rigid, semi-rigid, or non-rigid), and the installations possible.

Lightning Strike and Electrical Bonding Philosophy

Lightning strike is an ever present danger with airships, since they operate at altitudes with medium to high risk for lightning conditions. A combination of policies may be adopted, as follows:

- To protect rigorously all habitable, critical parts and systems, by electrically bonding each area via a common earth system and providing conduction paths leading to static discharge positions.

- To reduce the potential for a lightning strike attachment on critical parts - such as the: envelope, bow structure, empennage, bracing cables, gondola suspension cables, handling and control lines - by making them electrically non-conductive.

- Avoidance of regions of known adverse lightning conditions.

The first method is the conventional heavier-than-air craft manufacturer's approach, which, for such large structures (as with airships), increases the potential for a lightning attachment. This is due to the arrangement of bonding braids and structural parts that results from this approach, which offer numerous points with a high potential for a lightning attachment. Of course, if the airframe is predominantly metallic or is made from electrically conductive materials (such as carbon reinforced plastic) this method may be the only practical solution. Rigids built in the past needed this method owing to their vast metallic skeletal frames and long bracing or control wires. Critical structural parts and control lines should be made with sections able to carry the resultant charge without failure.

The second method is preferable, since it reduces the potential in the first instance. When lightning does strike it is then much more likely to make an attachment on a part with high potential, such as the gondola (which must have the first method applied to protect the occupants and avionic systems, etc), ignoring the rest of the airframe. Where electrical cables must be run (such as for navigation lights or power of control systems), these should be backed by earth braids capable of carrying the lightning charge and, where they run next to critical structures (such as a non-rigid's envelope), backed with insulation material to prevent burn through.

The potential for lightning conditions to develop is ever present and a pilot may inadvertently encounter these. Whilst the third method should be employed, to increase overall safety, it should be used in combination with the other methods to reduce the risk.

Factors of Safety

Generally, where materials and methods of construction are similar to those for heavier-than-air craft, factors of safety that must be applied in the design of the airframe are common. These largely depend on the certifying authority but can vary, depending on national standards and whether the airship is to be regulated under civilian or military codes of practice. The second and third references are typical civil authority national requirements for the UK and USA respectively, which have been developed and are now being utilised to help formulate the basic standards for the rest of the world. These standards define the various safety factors and other requirements that must be applied to the design of an airship.

In general, the authorities require that the maximum applied external (limit) loads be determined for critical flight or ground manoeuvres prescribed by them. The limit load is "the maximum load anticipated in normal conditions of operation" (second reference). These external loads must be placed into balance against inertia, including virtual inertia - which for an airship has a very significant effect - as appropriate. The structure's internal loads should then be determined, using a reliable approach (with known confidence limits), which does not underestimate the results. The material's appropriate proof (yield) and ultimate factors (typically 1.0 and 1.5 respectively for metallics - but beware of higher prescribed values on castings, cables, etc) must be applied in combination with other prescribed factors (such as fitting and form factors) as necessary. The resultant internal loads should then be compared with agreed allowable loads for the material's proof (yield) and ultimate (breaking) strengths, to ensure these are not exceeded.

For composite and other non-metallic materials, or where doubt may exist, the appropriate factors of safety should be determined in consultation with the relevant certifying authority. This is necessary to ensure an adequate level of strength remains throughout the airship's operational life, allowing for degradation in service.

For fabric structures particular to airship technology, an ultimate factor of 4 is usually required. This is necessary to account for uncertainties in the basic material's and assembled fabric structure's manufacture, degradation in service and creep rupture effects. It is also necessary to keep the material's residual stress level low, in order to avoid the possibility that an accidental tear might propagate rapidly (there being very few natural rip stopping members in a fabric structure).

In this respect, the basic material's tear strength must be maximised and should not be degraded owing to age or by service conditions (although it usually increases with usage). It is usually necessary to demonstrate the tear strength by test using large scale representative methods, as well as standard small pull tests - particularly where large volumes of pressurised gasses are contained - to prove that tears will not propagate.

Prescribed factors of safety (ultimate accelerations) on passenger seats, harnesses and the attachment fittings for general equipment installations vary markedly at this time between the different national airworthiness authorities. They are, however, significantly lower than for heavier-than-air craft, owing to the benign aspects of an airship's flight. Current ultimate acceleration factors (g's) for the UK and USA are given below (BCAR and US ADC):

Table 7.1. *Current ultimate acceleration factor (g's)*

	USA	UK
Downwards	3.0	4.5
Upwards	0.0	1.5
Forward	2.5	4.0
Rearward	1.0	4.0
Sideways	1.0	4.0
Max Resultant	N/A	4.5
Engines & Propellers	N/A	6.0

Hopefully these differences will be levelled in the near future. In addition a 1.33 safety factor is required on local attachment fittings for seats and harnesses.

Finite Elements

Finite element (FE) methods may usefully be employed to resolve redundancies and determine the internal loads, deflections, vibration characteristics, and the like, for an airship's conventional and essentially rigid structures, as paralleled within the heavier-than-air craft industry. These methods are now fairly common and can be studied in numerous literary works, so they will not be covered here. Special techniques and proprietary software, however, are needed in order to be able to use the method for fabric structures.

To analyse fabric structures properly and fully, using FE methods, the proprietary software must be capable of solving large displacement, non-linear problems. It must also have membrane elements able to take up complex double curvature shapes, that have bi-directional properties dependent on the loads applied, which only operate in tension and with minimal shear capability. In addition it must be possible to create the model from a notional idealised geometric shape, give it an initial pre-tension (modifying that shape, simulating pressure stabilised conditions) and then load it in stages to add: gravity, flight accelerations, external aerodynamic and internal gas pressure distributions, point load inputs, and the like - each loading stage creating new shapes and boundary conditions. Where fabric structures interact with essentially rigid structures, the software also must be able to handle the differences and provide methods (elements) which can be used to connect the two types of structure.

These aspects are necessary since, until a fabric structure has been pre-loaded (pressurised) it cannot act in its intended role and does not have a definable shape - being just a heap of crumpled material on the ground. When stabilised by pre-tensioning (pressurisation) a fabric structure takes up its working shape, which is different from the idealised shape used for its initial design and manufacture. Successive load inputs then modify this shape. These shapes are created by initially running an idealised model with stabilising pre-loads to produce output that can be used as input for a new model, upon which the other loads can be applied - the procedure being repeated for each load step.

A basic assumption of the above is that the assembled fabric structure initially conforms with the idealised shape. This is not true if it has complex double curvature (as for envelopes and ballonets), since the fabric gores are cut from flat strips. Approximations, difficult to model, inevitably arise in order to construct the item. When pre-tensioned (pressurised) local stresses are created in the fabric membrane owing to such approximate methods. It is assumed that these are negligible if the fabric material has compliant properties and the number of gores used in the assembly is optimised to reduce the anomalies to a minimum.

Clearly, validation of such FE models is a necessary step, to ensure that the results generated are within acceptable limits before using them in the design process. Physical tests on representative fabric structures, which are also modelled using the FE methods intended for the design process, should be undertaken to validate the modelling techniques and proprietary software`s ability to predict the results accurately. Following such tests comparisons with the results of test and FE models should be made to establish confidence and use limitations. Having established confidence in the FE method, models of simple fabric structures may be created, which are easily validated by standard methods - gradually building confidence for larger more complex models.

The remaining part of this chapter concentrates on structural designs for non-rigid applications.

PRINCIPAL STRUCTURAL GROUPS

The primary structures of a non-rigid airship may be grouped under the following headings: envelope or hull; gondola or car; gondola support system; tail group; nose structures; landing gear; propulsion structures. Except for the last item (propulsion structures), the design methods of which are common with other aircraft and can be studied in numerous literary works, the design of each group will be discussed in the sections that follow.

Envelope or Hull

Most of the recent non-rigid, helium filled airship envelopes, have been made from a coated fabric and/or laminated fabric/film material produced in roll form. These materials have been designed to contain the lifting gas under the loads imposed by flight and to endure the extreme environmental conditions of the airship`s operational regions. The basic material is cut and adhesively jointed to make a bag for gas containment, which is pressurised with air to stabilise and maintain its aerodynamic body of ‘revolution’ shape.

The finished envelope is normally designed - using a single membrane - to contain the lifting gas, with integral internal ballonets (sacks or bladders) for the pressurising air. As an alternative to this method some airships have been designed using an outer structural fabric envelope, pressurised with air, with a separate inner bladder of film material, similarly shaped, to contain the lifting gas.

The ballonets are made from a similar but lighter, thinner material to contain and keep the air from mixing with the lifting gas within the envelope. They are filled via an external supply system to pressurise the envelope.

The envelope’s super pressure (i.e., the pressure at the lowest element of the largest cross section) must be maintained to prevent the envelope from loosing rigidity (becoming limp) - as height, temperature or atmospheric pressure changes - by allowing the proportion of ballonet air to vary, compensating for the volumetric changes of the lifting gas. Thus air (which is freely available) instead of the lifting gas, may be added or exhausted to maintain constant envelope pressure.

The ballonets may either be separate bags within the envelope, restrained by a cable system to load patches, or be integral with the envelope via an upper membrane continuously attached around its perimeter; with the envelope for its lower surface, to form individual airtight compartments. The first method may appear to be attractive from a maintenance point of view (since they are easily replaced) however, they are heavier (the envelope is there anyway). Separate ballonets are also more difficult to restrain if unwanted movement (slosh) occurs and the surface area inside the helium space is doubled increasing leakage rates.

The ballonets are normally located against the envelope's lower surface, since air - being much heavier than the lifting gas - tries to find the lowest level (like water mixed with oil). When designing the ballonets this effect must be considered in order to prevent ballonet slosh, otherwise, as the airship pitches, large movements changing the airship's trim may occur. In a dive, if the ballonet air sloshes forward - trying to find the lowest level - then the lifting gas will move aft to fill the void, causing the centre of buoyancy to move aft. If not kept within reasonable limits this effect could compromise the pilot's ability to right the airship, tending to steepen the dive. If the ballonets are not properly shaped then some form of restraint will be necessary to prevent such slosh, increasing the weight of the system.

The ballonets' positioning on the lower surface is of benefit when considering the effects of damage from projectiles in minimising the potential for lifting gas leakage. The ballonets should also be positioned to avoid slosh against internal cables (such as gondola suspension) and other components within the envelope, to avoid abrasion damage. The air supply trunks should also be as short and straight as possible to minimise system losses.

The size of the ballonets is dependent on the maximum altitude the airship is expected to fly at and the ambient temperature of the local region. Typically, they may be expected to have a maximum capacity of around 25 to 40 percent of the envelope's gross volume, although they must be designed to collapse totally without straining the envelope at the pressure altitude (the altitude at which the lifting gas completely fills the envelope's volume). If integral ballonets are fitted then additional slack must be provided in the ballonet material to allow for the envelope's expansion under load (the ballonets being pressed against the envelope and forced to adopt its profile), otherwise they will restrain the envelope causing stress concentrations and picking up load themselves.

The number of ballonets may range from one to four. For a small airship one ballonet may be considered sufficient, if there is no interference with the gondola's suspension system. Medium or large airships of low altitude can take advantage from siting two ballonets, one forward the other aft; thus, by shifting air between them (allowing one to inflate while the other collapses) the centre of buoyancy of the lifting gas can be moved to effect a change in trim. This can only be done near to the ground, since at altitude the ballonets are nearly empty; thus enabling the airship's balance to be adjusted for landing or take-off when aerodynamic control may be poor owing to low flight speed. For an airship of high altitude needs and/or in hot climates a large ballonet capacity may be necessary. In this instance the additional capacity can be provided via pannier ballonets each side.

The pressurisation system of a non-rigid airship is very important, since this is what maintains the envelope's ability to perform as a structure. A dual system, with independent trunks, fans and controls, etc, should therefore be considered, to ensure the envelope's working pressure is always maintained. In addition a means to pump air directly into the lifting gas area is needed to pressurise the envelope under emergency conditions. This may occur if the envelope is holed (for whatever reason), enabling the lifting gas to escape. Under such conditions the ballonets inflate until they are full. When full they can no longer expand freely to pressurise the envelope, and thus become ineffective.

Under normal conditions the differential pressure across the ballonet membrane is very small, reaching a maximum at their lowest point (where the head of air is greatest). This is particularly important for the design of pannier ballonets. Slosh increases the pressure, owing to the dynamic effects that occur when the moving mass of air is stopped by the ballonet's membrane. The ballonets' design pressure, however, is normally established from their full condition, since, if the fans are left running with the valves locked and closed, they merely serve to pressurise, tending to burst the ballonets. Because of the power of the fans (required to overcome resistance along the trunks and deliver air to the ballonets) the pressure developed by them is usually an order of magnitude greater than normal operational conditions within the ballonets and envelope. Care must be exercised in the hangar to avoid rupture of the ballonets if, for maintenance purposes, other, more powerful, fans are used to maintain the airship's pressure.

The air supply rate to the ballonets must be designed to maintain constant envelope pressure under the airship's maximum rate of descent and/or expected extremes of climatic change, compatible with the volume of the envelope. This invariably requires an air supply system with powerful fans to cope with the vast quantities of air that need to be moved. Tapping air from behind the airship's main propellers, using scoops located in the propeller wash, and then ducting it via trunks is the most convenient way of supplying the air under pressure to fill the ballonets. Auxiliary fans, however, are also needed to deliver air when the propellers are not functioning, vectored out of line from the scoops, in reverse thrust mode or at low power.

Retractable scoops may also be fitted so that propeller efficiency is not degraded when the envelope's pressure is stable (which should be most of the time). If more than one ballonet is fitted, a distribution system is also needed to direct the air to particular ballonets.

In order to reduce the volume of entrapped air within the ballonets, large valves must be installed to release the air under the envelope's pressure into the surrounding atmosphere. This is necessary in order to maintain a constant envelope pressure when ascending or owing to increases in pressure from changes in weather. These valves must open automatically as well as manually and be able to operate at different pressure settings, as conditions dictate, to regulate the envelope's pressure. High envelope pressures are needed for turbulent weather and rapid manoeuvres, whilst lower settings may be adopted for hangar use and calm conditions. The ability to lock valves with low settings enables higher operational pressures to be maintained.

Similar vent valves are needed to relieve envelope pressure directly, by releasing the lifting gas to atmosphere. These safety relief valves need to operate automatically after the ballonets have completely deflated when pressure is rising above acceptable limits for the envelope. The relief valves also require manual override to test their function, which may also be used to enable a balloon landing or flight control under emergency conditions.

The gas pressure relief valves should be located at positions that enable the lifting gas to be released efficiently but without the possibility that all of the gas could escape, should they leak or fail to close (which could occur if they are sited at the top of the envelope). This is a danger, since they are only operated infrequently with the consequent danger that they might seize or stiffen through lack of use. The designer should therefore pay particular attention to the valves' details to ensure reliability in service.

Since the flow rate through these relief valves may be high, to prevent the danger of losing too much gas, should they fail to close (which not only reduces the buoyancy but also compromises the ability to maintain envelope rigidity - owing to the ballonets' capacity, when full, to compensate for the lost gas volume), small gas vent valves may be installed for control purposes under conditions of free-balloon flight. These valves should be designed so that if they do fail open or leak, the rate of flow through them is small, such that continued flight is prolonged, making a safe landing possible.

Inevitably the various valves and fittings require penetrations in the envelope. The envelope therefore must be reinforced to enable the fabric tensions and resultant stress concentrations to be carried around the resultant holes. In addition, owing to hoop and longitudinal stress differences, the envelope's fabric tensions are variable around the penetration. A stiff edging ring is therefore also needed to maintain the hole shape. Since the valves are fitted to these penetration positions they must be able to accommodate resultant distortions without affecting their operation and performance.

The continual supply of air to and release from the ballonets, causes them to rise and fall frequently. This flexing, together with flexure owing to slosh, places a heavy duty on the material and its joints - particularly, for integral ballonets, at their intersection with the envelope. Materials with a high flexural and gas retention capability are therefore needed to overcome associated problems. The additional materials of the ballonets' joints with the envelope also introduces stress concentrations, owing to the inevitable increase in envelope stiffness at these positions. Orientation of material and graduation of reinforcing plies or jointing tapes should therefore be optimised to reduce the stress concentrations to a minimum.

To calculate the pressure required for maintenance of envelope rigidity in flight the maximum applied bending moment must be established. To do this the aerodynamic loads on the envelope and empennage must be put into balance against the mass distribution (including concentrated loads from the tail, gondola and nose structures) subject to gravity and the accelerations resulting from flight manoeuvres or gusts, buoyancy (not forgetting to subtract the ballonet effects), thrust and drag, etc. and then integrated along the length to determine the maximum value. The lifting gas static head effect (pressure gradient from bottom to top) also must be taken into account.

Empirical formulae for the determination of the maximum bending moment in flight, as a short cut to the above, have been used in the past (Burgess, 1927), The FAA (US

ADC) also provide a formula, as given below, which may be used by the designer in the absence of a more rational analysis. It is recommended that these formulae only be used as a check, to validate a dynamic analysis of the airship's flight envelope (from which the maximum bending moments may be derived).

FAA bending moment formula:

$$M = 0.029\{1 + [L/d - 4][0.5624L^{0.02} - 0.5]\}\rho.u.v.V.L^{0.25} \tag{7.1}$$

Applicable for L/d between 4 and 6. For $L/d < 4$, use 4.

Where:

L	=	Length of airship (ft).
d	=	Maximum envelope diameter (ft).
ρ	=	Density of air (slugs/cu.ft).
u	=	Gust velocity (ft/s).
v	=	Airship equivalent speed (ft/s).
V	=	Total envelope volume (cu.ft).

Note: Gusts of 25 ft/s, while flying at the maximum level flight speed at sea level, and 35 ft/s, while flying at the design speed for maximum gust intensity should be considered.

To maintain rigidity the envelope must remain under positive tension when subject to the maximum bending moment combined with other compressive load inputs. Assuming that engineers' theory of bending is valid and the envelope's cross section is a circle of radius 'r' one may write:

$$f_2.t = M.r.(t/I) + (T - p.(\pi.r^2))/(2.\pi.r) > \text{or} = 0 \tag{7.2}$$

for rigidity.

Where:

f_2	=	Longitudinal membrane stress.
t	=	Membrane thickness.
M	=	Maximum bending moment, including pressure gradient effect.
I	=	Membrane second moment of area.
T	=	Thrust.
p	=	Envelope super pressure.

$\pi \quad = \quad 3.142.$

For a circular membrane of large radius it can be shown that:

$$I/t = \pi.r^3 \tag{7.3}$$

The minimum pressure (p_{min}), where rigidity is just maintained (without a kink developing), may be calculated from the condition for $f_2.t = 0$. Re-arranging and substituting for I/t we can therefore write:

$$p_{min} = 2.M/(\pi.r^3) + T/(\pi.r^2) \tag{7.4}$$

Neglecting thrust and re-arranging, the bending moment 'M_k' which just overcomes rigidity (kinking the envelope) may be defined as:

$$M_k = (p.\pi.r^3)/2 \tag{7.5}$$

Note: engineers' theory of bending has been shown by test to be valid for non-rigid airship envelopes to a reasonable degree of accuracy, so the above formula is valid (Burgess, 1927).

Having determined the pressure, material for the envelope's manufacture may be established by treating the envelope as a cylinder and applying pressure vessel theory,

where: Hoop tension, $f_1.t = p.r$

Note: When dealing with fabrics membrane stress is a meaningless term, since fabrics are made from individual fibres instead of a homogeneous material. Thickness, if used, is an idealised term - which may be necessary for certain computing techniques. The term 'f.t' is therefore used instead, being the load or tension per unit width, which can be determined by ordinary test techniques.

If the bending loads overcome rigidity then the envelope will collapse, a kink developing as shown in Figure 7.2. When, however, the load is removed the envelope normally pops back into shape without any damage and is then able to perform as a rigid structure again. This phenomenon is very useful if accidental overload occurs, since the structure suffers no permanent damage, enabling the airship to continue flying. How many other aircraft, after being subjected to such overloads, could continue as normal? Clearly this behaviour warrants further investigation.

When the envelope kinks a wrinkle develops around the cross section from the point where the membrane tension is reduced below zero by the bending effects, as shown in Figure 7.3 (without breaking or releasing the lifting gas), until a stable position θ is reached where the tension becomes positive again.

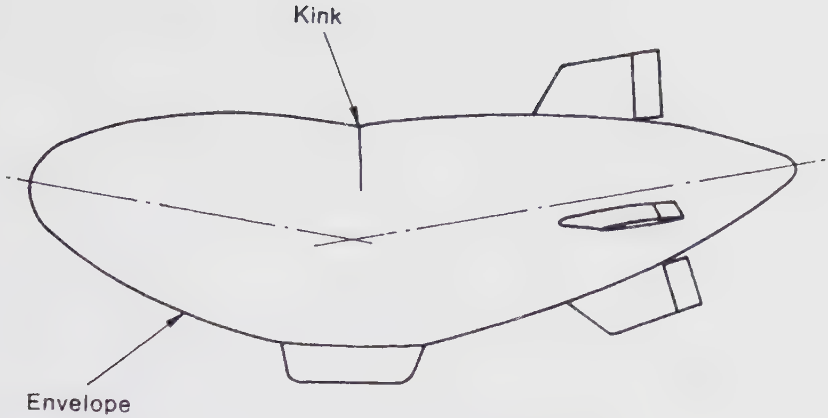

Figure 7.2. Kinked envelope owing to lack of rigidity.

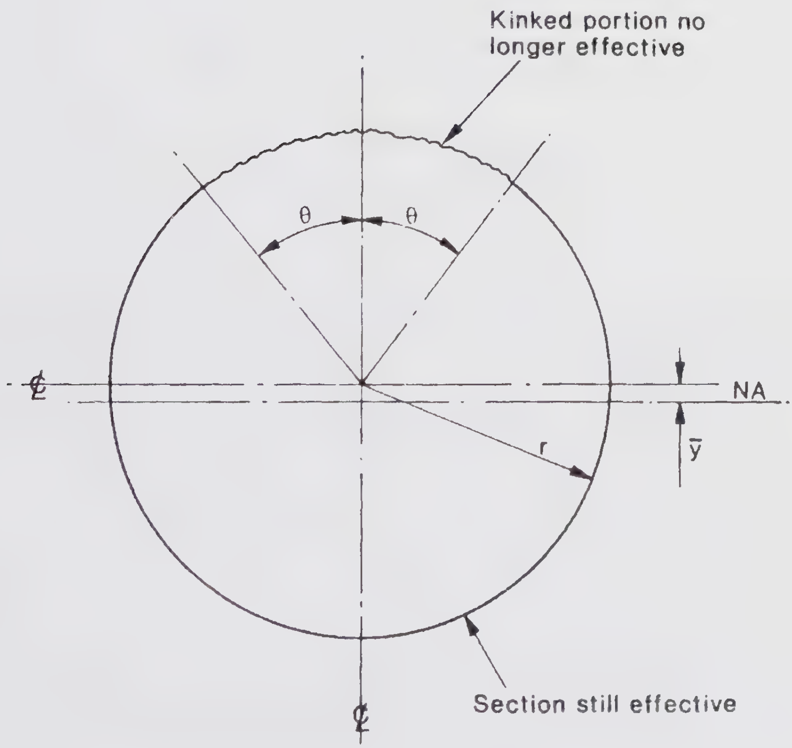

Figure 7.3. Extent of kink around the cross section.

Assuming that engineers' theory still holds true and the cross section remains circular, the effect may be treated as follows: the wrinkled portion of the envelope is no longer effective, so it should be removed from calculation of the section constants. Revised section properties may be established from:

$$I/t = r^3.[\pi - \theta + (\sin 2\{\pi - \theta\})/2 - 2(\sin^{2\{\pi - \theta\}})/(\pi - \theta)] \quad (7.6)$$

and the position of the section's neutral axis is:

$$NA = r(\sin\theta)/(\pi - \theta) \quad (7.7)$$

below the section's centre.

The centre of pressure, however, remains at the section's centre. Neglecting thrust, for equilibrium we may therefore write:

$$P/(2.r.t.\{\pi - \theta\}) + P.NA.(r.\cos\theta + NA)/I = M.(r.\cos\theta + NA)/I \quad (7.8)$$

Where: $P = p.\pi.r^2$

Hence, re-arranging and substituting for P we can therefore write:

$$M/(\pi p r^2) = \frac{\pi - \theta + \cos\theta - \sin\theta}{2\left[\sin\theta + (\pi - \theta)\cos\theta\right]} = k \quad (7.9)$$

From a Plot of θ against k, as shown in Figure 7.4, we may easily determine bending moments demonstrating that, while the envelope may have kinked it is still able to resist bending. In fact, when:

$$\theta = 180 \text{ degrees}, k = 1 \quad (7.10)$$

Therefore:

$$M = p.\pi.r^3 = 2.M_k \quad (7.11)$$

Clearly, an envelope that has kinked to such an extent is not feasible, the theory having broken down owing to non-linear effects. To examine the theory further the longitudinal tension (f_2.t) at the envelope's opposite face will be examined.

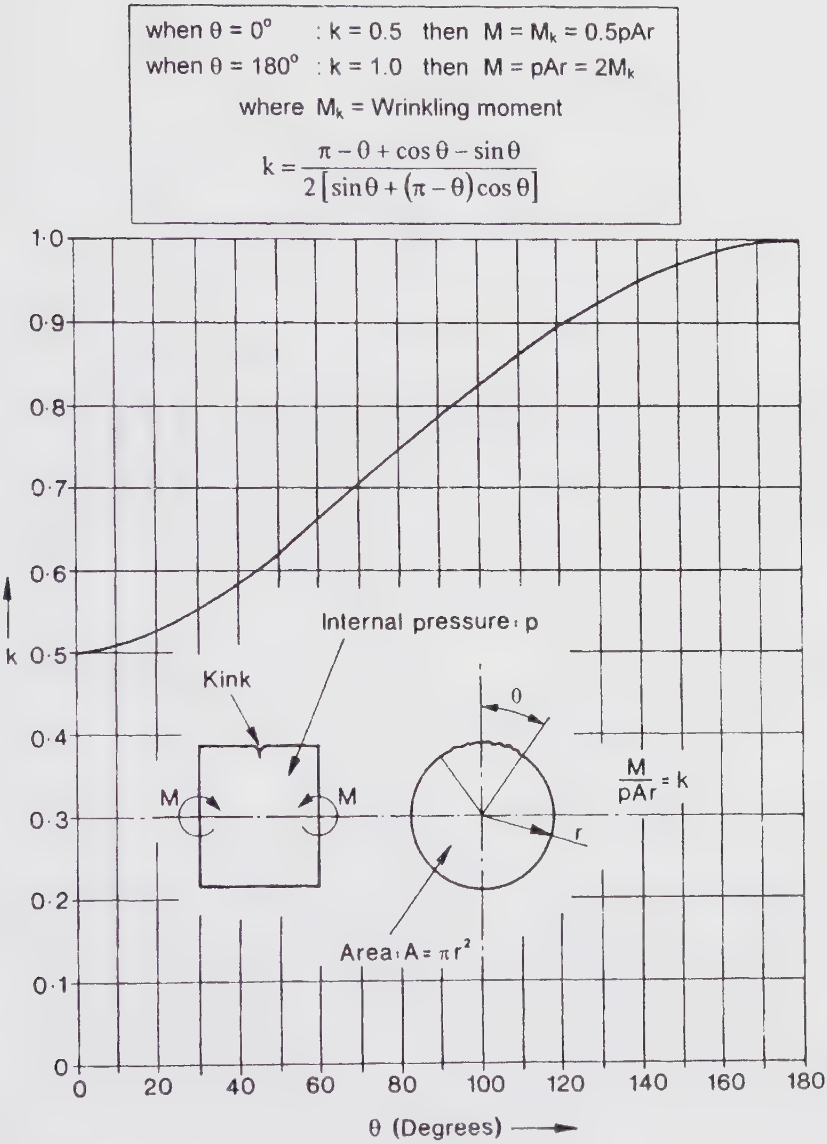

Figure 7.4. Graph of θ against k - Theoretical buckling of flexible cylinder under internal pressure due to applied bending moment.

Similar to the above, for equilibrium we may write:

$$f_2 = M.(r - NA)/I + P/(2.r.t.\{\pi - \theta\}) - P.NA.(r - NA)/I \tag{7.12}$$

Also, from above:

$$M = P.r.k \tag{7.13}$$

Hence, substituting for P, I, NA, M and k, and re-arranging we get:

$$f_2.t/(p.\pi.r) = [(1 + \cos\theta)(\{\pi - \theta\}^2 - (\{\pi - \theta\}.\cos\theta.\sin\theta) - 2\sin^2\theta)]/[2(\{\pi - \theta\}.\cos\theta(\{\pi - \theta\}^2 - (3\sin^{2\theta}) + (\sin^{3\theta}(\{\pi - \theta\}^2 - 2)))] = K \tag{7.14}$$

From a plot of θ against K, as shown in Figure 7.5, we may easily determine the longitudinal tension. However, as the Figure demonstrates, beyond about 110 degrees the tensions rise by an inordinate amount - approaching infinity at 180 degrees. This cannot be, since either the material would have failed (unlikely) or other non-linear effects would have taken over, the original assumptions no longer being valid.

When, $\theta = 0$, $M = M_k$ and $K = 1/\pi$

Therefore, $f_2.t = p.r = f_1.t$

When, $\theta = 110$ degrees, $K = 0.63 = 2/\pi$

Therefore, $f_2.t = 2.p.r = 2.f_1.t$

The above is offered to raise awareness of the potential benefits and effects of pressure stabilised envelopes, but does not purport to be a complete theoretical approach. Testing to determine the limits for which it may be valid needs to be done before relying on values determined from it. With the availability of powerful non-linear large displacement finite element tools, able to handle fabric structures, a more accurate approach might be developed.

The envelope may be manufactured from strips of material (known as gores) either running longitudinally, like orange peel strips, or circumferentially - both techniques having been used previously. Whichever method is adopted, approximate methods need to be employed to determine the gore's shape for cutting, since the material is manufactured flat and then is forced by internal pressure to adopt a shape with double curvature. Clearly, this introduces stress concentrations (straining some areas more than others), which should be kept to a minimum.

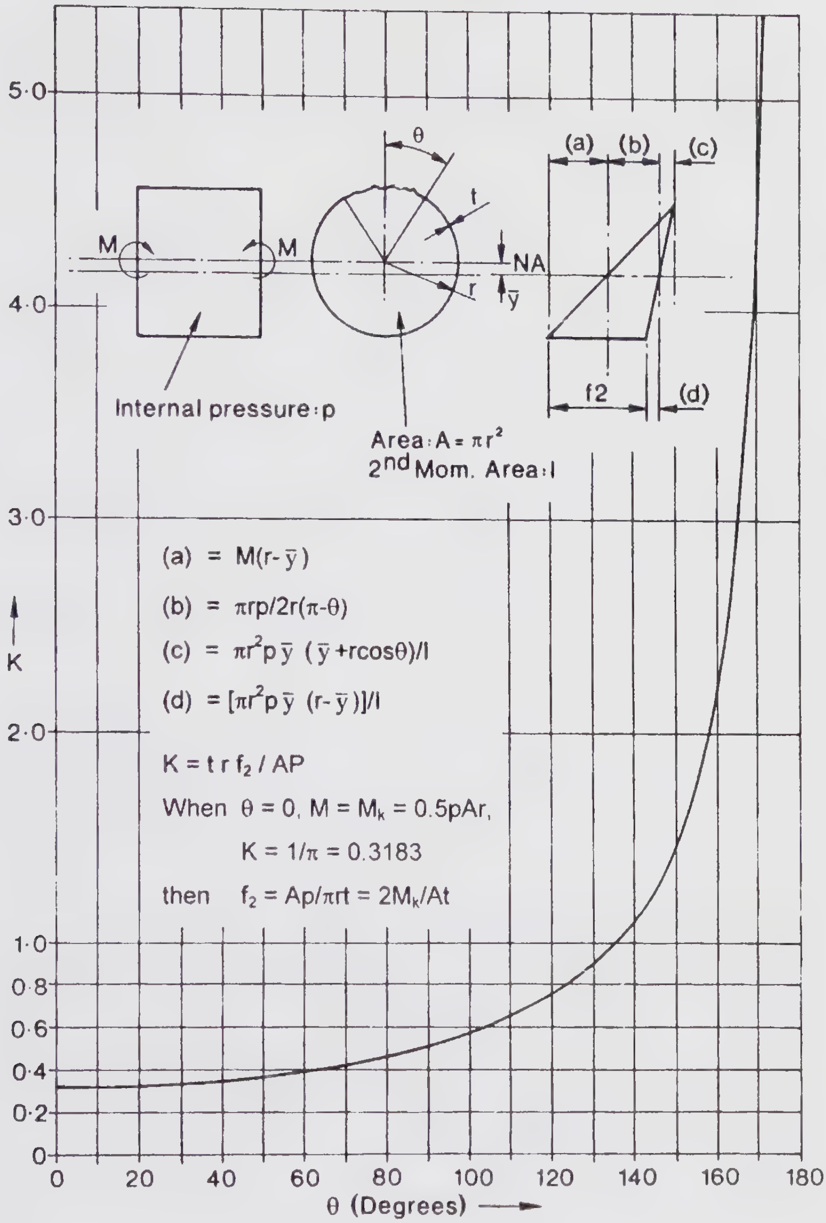

Figure 7.5. Graph of θ against K - Theoretical maximum tensile stress of inflated tube in port wrinkling regime.

A compliant fabric should therefore be used. When determining the gore's width (apart from restrictions owing to available supplier widths) a balance needs to be struck between the number of joints (which should be minimised) and the strain induced (which reduces as the number of gores is increased).

The seams should be designed to develop the full strength of the fabric being joined, and be gas tight (unless a separate gas bladder is employed). Modern fabrics may be laminated with films (to provide a gas seal), which usually are difficult to bond to and have poor peel strengths from their base fabric. As a result it may only be possible to join the envelope material from one side. Modern adhesives, however, can now be used to make the joints without stitching; provided a comprehensive test programme has been undertaken, which demonstrates the various joints integrity under all conditions of service. Quality control and cleanliness during manufacture is of the utmost importance, to ensure the actual joints meet the required standard.

A typical joint may be made by butting adjacent gores together with a small gap (about .030") between them, to prevent a ridge from forming when joined. The joint is made using a structural tape bonded on the strength side, the side of the material which produces the best joint (usually, for a laminated material, the opposite side to the gas retention film). In addition, a light non-structural tape employing film material on the opposite side may be necessary to restore the gas seal. The structural tape may use material of similar construction to the basic envelope, but without the film material. The various jointing tapes should be of material cut on the bias (+/- 45 degree), to enable the joint to expand with the envelope. In addition, the jointing tapes (structural and gas seal) should be of differing widths to reduce stress concentrations at their edges.

Longitudinal gores have their fabric's weft threads, which weave in between the more straight warp threads, running circumferentially. If the envelope is treated using cylinder theory then the circumferential or hoop tensions are twice the longitudinal tensions. As a result, when the envelope is pressurised these threads try to straighten against the warp threads (which are bent by this action) as well as stretch under load. The effect of this is that, when pressure is applied, overall length changes may be small while the diameter may enlarge significantly. If the gores are circumferential then both longitudinal and diametrical changes may be expected. These effects must be taken into account when determining the envelope's final volume and the position of components on and interfaces with the envelope.

Assuming the envelope to be a body of revolution, with form derived from a polynomial expression $y = f(x)$, its geometrical attributes may be determined from the following standard mathematical formulae:

$$\text{Volume} = \pi.\int y^2 dx \tag{7.15}$$

$$\text{Prismatic Coefficient} = \pi.r^2.\text{length/Volume} \tag{7.16}$$

$$\text{Centre of buoyancy} = (\pi.\int x.y^2 dx)/\text{Volume} \tag{7.17}$$

$$\text{Surface Area} = 2.\pi\int y.(\{1+[dy/dx]^2\}^{(1/2)})dx \tag{7.18}$$

$$\text{Centre of gravity} = (2.\pi\int x.y.(\{1+[dy/dx]^2\}^{(1/2)})dx)/\text{Surf Area} \tag{7.19}$$

$$\text{Longitudinal surface length} = \int(\{1+[dy/dx]^2\}^{[1/2]})dx \tag{7.20}$$

For circumferential gores, Blakemore (1927) gives a method to define the shapes to be cut. For longitudinal gores a simple patterning method may be established, treating the envelope as a body of revolution, from the following procedure:

- Divide the envelope along its axis into a number of stations (i).
- For each station (xi) calculate the radius (yi) of the section from the polynomial expression $y = f(x)$ for the envelope's shape.
- For each station (xi) calculate the longitudinal length (si) along the surface to the station using the expression above.
- For each station (xi) calculate the gore's half width from the expression $wi = (\pi/n).yi.(1-\{p.yi/[E.t]\})$, where n is the number of gores and [E.t] is the fabrics modulus.
- Plot si against + and - wi to define the gores shape.

Note:

- The term $(\pi/n).yi^2.p/[E.t]$ is a reduction term to allow for the envelope's expansion under internal pressure, otherwise the volume (and hence buoyancy) would be too much.
- For an envelope shape with rounded ends the expression for longitudinal surface length cannot be calculated, owing to singularities at these positions. As a result approximate methods at each end must be used to overcome the problem.

Gondola or Car

The gondola or car is an aerodynamically shaped vessel, similar in principle to the fuselage of heavier-than-air craft, provided to house the crew, passengers and airship's general systems. (Chamberlain, 1984), the term gondola may arise from early Zeppelin terminology owing to their boat-like appearance. Certainly, some previous airship gondolas have been used to enable airships to settle on water (Williams, 1974); an attribute that may be deemed highly desirable.

A single gondola has been the norm for non-rigid airships, although separate nacelles may be used to help spread the subsequent concentrated load over the envelope's lower surface. Rigid airships of the past have taken advantage of this option, providing separate engine or power cars. Separate cars enable noise and vibration to be isolated from the habitable areas and provide a wide disposition for propeller and undercarriage units. However, access in flight needs to be provided to each nacelle if long endurance flights are envisioned; balance is more difficult to maintain as fuel is used or other variable loads are disposed; cabin heat, power distribution systems and lightning strike protection is more difficult to co-ordinate/devise. Placing as many systems as possible into a single gondola is the most convenient option and, from a weight/drag aspect, is more efficient, although the suspended mass is difficult to carry without noticeable envelope distortions.

As airship size increases the proportion of gondola suspended mass to the overall airship mass increases, the gondola becoming more of a burden to support. At the same time the envelope's ability to support the suspended mass without significant distortions occurring diminishes with increased size.

In simple terms, this is because the envelope's ability to support the gondola's suspended mass is proportional to fabric tension (i.e., proportional to 'pxr'), whilst the gondola suspended mass is roughly proportional to gas lift (which in turn is proportional to envelope volume, i.e., proportional to 'r^3'). So, if 'r' is doubled the suspended mass is increased by a factor of 8. At the new size the pressure required to maintain rigidity increases by a factor less than 2 (mainly due to higher speeds). The envelope's ability to support the gondola's suspended mass therefore only increases by a factor of 4. Overall, the envelope's ability to support the suspended mass is therefore diminished by a factor of 2. As a result the gondola's length becomes increasingly important, to be able to spread the load over a sufficient length of the envelope.

Since the gondola's depth is roughly controlled by human proportions (the same for any sized airship) its length to depth ratio rises, reducing rigidity and increasing bending stress levels. This can be offset by making the gondola double decked, but at the expense of concentrating mass (making the suspension system more difficult to design). Clearly, compromises are necessary as size increases to optimise the airship's overall design.

Depending on overall configuration, the gondola may be designed to carry the propulsion and power units, fuel, ballast, water recovery system (if used), landing gear, electrical systems, avionics, envelope air supply, furnishings, general equipment, mission and other systems of the airship. As such it is the working centre of the airship and so should be designed for a variable interior arrangement. It should be located such that when fully laden the suspended weight centre of gravity (cg) is roughly below the lifting gas centre of buoyancy (cb). Variable masses (fuel, ballast, crew and passengers, etc) should be located within the gondola to maintain overall airship balance.

The type of gondola provided depends on whether cabin pressurisation is required for the crew and passengers at altitude, since this has a dominating influence on the structure. If pressurisation is required then a car of circular form is needed to optimise the structure as a pressure vessel. This shape is awkward to work with, since it does not conform to the envelope's profile (also of circular form), making the interface complicated and the support system difficult to configure. Inevitably there is also a weight penalty, since the structure has to be stronger with increased complication/parts count and more difficult utilisation of space compared with an equivalent non-pressurised car.

In an attempt to ease the problems of envelope interface and space utilisation the pressurised car may be shaped as shown in Figure 7.6a. It must be recognised, however, that as a pressure vessel this shape is not ideal. This is because it only partially works in membrane tension - imposing greater bending loads on the primary members and joints to hold the shape as it tries to become circular. Optimisation exercises looking at aspects of overall airship design - not just structural - need to be run to determine the best shape. For a non-pressurised gondola much more simple shapes may be adopted, extending up to nest against the envelope, as shown in Figure 7.6b.

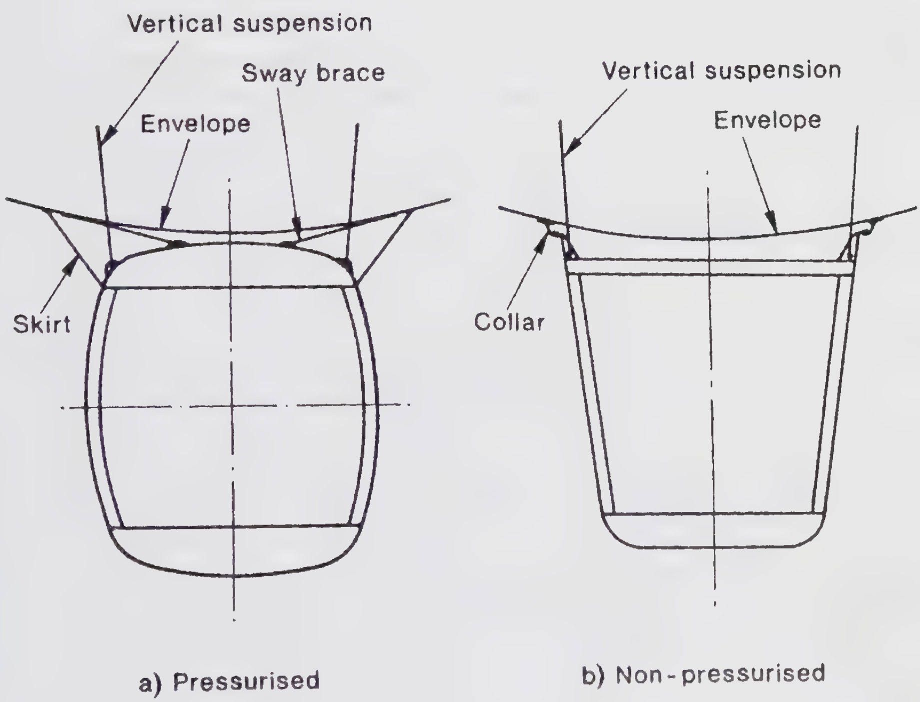

Figure 7.6. Gondola cross sections.

The type of gondola structure is heavily dependent on the airship's role. Examples of different roles and how they affect the gondola's design are given below:

Ex. 1 **Small airship for pilot training.** The gondola of such an airship may be of simple construction, essentially a faired bedstead frame with cockpit to mount the necessary systems and accommodate the instructor with his trainee. No passenger accommodation is necessary. Thunder and Colt's GA-42 may be used to illustrate this category.

Ex. 2 **Medium sized airship for sightseeing purposes.** The gondola for this role should be configured with a comfortable sized cabin, with large panoramic windows, to accommodate a passenger seating arrangement with galleys and toilets, etc. Standard seat tracks should be fitted to allow variability between customers. To aid the passengers' sense of well being, the structure should have a good appearance with a feeling of security about it. It should also be able to handle general abuse. Airship Industries SKS 600 series serves to illustrate this category.

Ex. 3 **Medium sized airship for para-military surveillance duties.** This is similar to Ex 2 but not so fussy on creature comforts. Seat tracks are still required, but are used more to mount customers equipment. Additional hard points may also be needed to mount special items, such as radar antennae, camera pods, search light, rescue winch, etc. Also, extra apertures may be necessary and doors widened to accommodate special needs. Westinghouse Airship Inc's Sentinel 1000 illustrates features for this type of airship.

Ex. 4 **Large oceanic airship for patrol purposes.** This may be a scaled up version of Ex 2 and 3, which also should provide: hotel-like accommodation for extended length flights, large capacity fuel and ballast tanks, a cargo deck with large floor aperture and winches for inflight replenishment. The projected design for the US ODM programme, designated YEZ-2A is an example of such a design.

Standard structural techniques, taken from the heavier-than-air craft industry, should be employed for the gondola's design. These can be studied in various literary works on the subject: Bruhn (1973), Peery and Azar (1982) and Niu, (1988) being just a selected few.

Gondola Support System

Early designs (Abbott, 1989) adopted an external method of support from finger patches on the envelope's lower surface with the gondola suspended below, using cables. This method had a number of merits, such as:

- Simple concept - easy to install rig and maintain - that does not require envelope penetrations or entry, which otherwise would require breathing apparatus and cause additional complication.
- Easy to remove/install or switch gondolas, enabling modifications to be undertaken in convenient workshops or new marks to be fitted.
- Substantially reduces landing load inputs, since the gondola is separated from the envelope and the suspension cables can go slack, preventing load transmission from the envelope.

In order to spread the gondola's suspended weight over a sufficient area of the envelope's lower surface and provide an essentially tangential input, the gondola was generally underslung some way below. This introduced disadvantages, to be weighed against the above, as follows:

- Overall airship height increased, requiring taller hangars and masts.
- Makes interfaces for necessary controls and systems difficult to configure.
- Increases drag (lowering overall airship performance) owing to greater gondola wetted surface area, gondola outside the envelope's boundary layer, large total length of cable across the airflow and interference effects between the envelope and gondola.
- Limits permissible pitch attitudes owing to cables going slack.
- Lowers overall airship centre of gravity, increasing pendulum stability, making the airship more difficult to manoeuvre. As a result larger (more powerful) control surfaces are needed to overcome the effect.
- The gondola cannot easily be used to mount large mission system antennae - a feature which may be desirable for current surveillance duty objectives.

Current airships have sought to redress these problems by configuring the airship with a close-coupled support system, enabling the gondola and envelope to nest together. Some airships have even placed the gondola (ZPG-3W, designed by Goodyear in the 1950s) partially inside the envelope via a large aperture. The resulting configuration largely depends on the airship's role, size and gondola section profile.

For small airships (60,000 cu ft - 1,700 m^3) configured for light aerial duties (advertising and/or camera platform) of short endurance (8 hours) the gondola's suspended mass is a small proportion of the overall airship mass, the fabric tensions are proportionately large, and limitations on all weather applications may be imposed (compared with medium or large airships). As a result a simple external support system may be considered, as utilised by the American Blimp Corporation's A-60 Lightship.

Larger airships require a disproportionately bigger footprint to carry their gondola's suspended mass, which is difficult to provide on the lower surface. An internal suspension system, supporting the gondola from the envelope's upper surface, may be used to overcome the footprint problem, since it uses the envelope's large diameter to allow the load to be spread over a wide area. If the cable splay is limited to about 15 degrees from vertical then the resultant compression over the envelope's upper surface will not overcome the membrane tension.

Essential features of a typical close coupled support system are:

- Internal suspension cable system, which essentially reacts to the gondola's vertical weight.
- Gondola to envelope lower surface interface connections, which react to the gondola's horizontal shear forces.

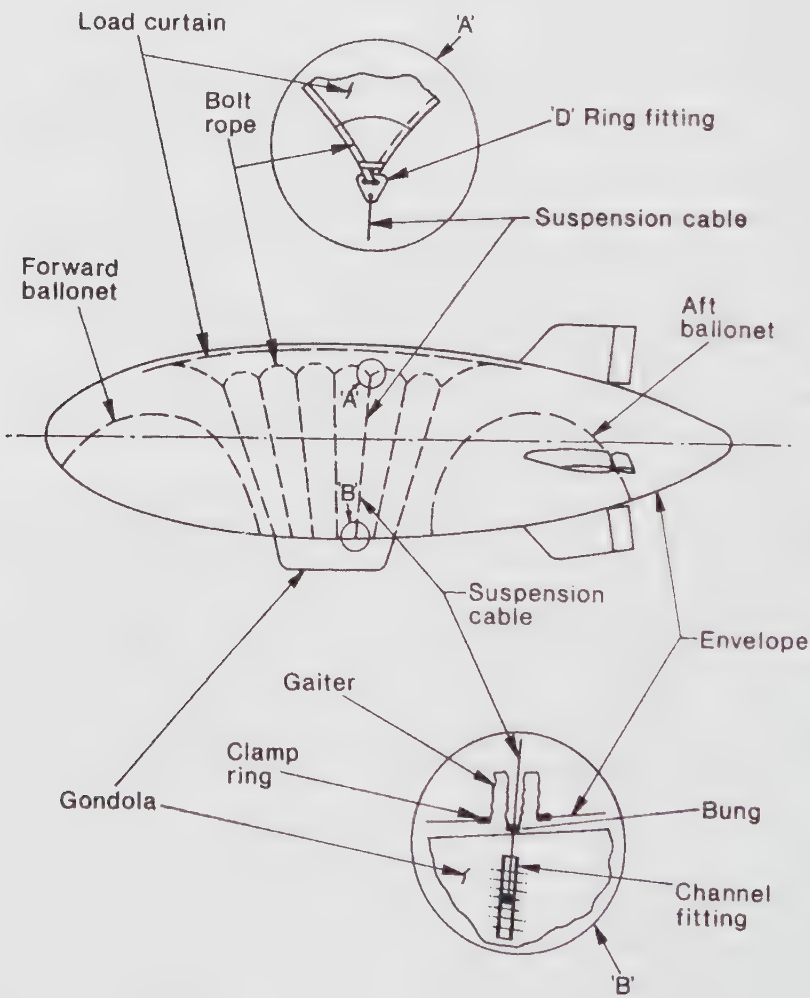

Figure 7.7. Typical close coupled support system.

As shown in Figure 7.7 the suspension cables are connected to fittings along the gondola's upper sidewalls. They are then passed through gaiters in the envelope's lower surface, which accommodate interface movements and seal the envelope. The cables then pass on up to arched load curtains, which in turn transfer the load to the envelope's upper surface.

The arched load curtains are longitudinal fabric structures hanging from the upper envelope, essentially acting like inverted suspension bridges, which should be designed to spread the cable loads evenly along their length. The input cable loads, which connect at the cusps, are fed into the curtains via continuous bolt ropes (load tapes) along their lower edges. These can also be backed by finger patches at the cusps, as necessary. Adjacent cables along the length tend to balance between themselves around the bolt rope, similar to a rope over a pulley. At each end, however, the unbalanced bolt rope load must be reacted by load patches into the envelope.

The incoming cable should bisect the cusp angle equally, to prevent excessive load on one side of the cusp. In addition the included angle of each cusp should be made acute, to minimise the load in the bolt rope and prevent load entering the curtain too quickly. To assist the latter point, the bolt rope (load tape) should be of high modulus material so that the load remains in it over a longer length.

The number of load curtains depends on the cable array, which may bifurcate or combine at different stages to help reduce the inputs at the attachment points. If more than one (two total) curtain for each side of the gondola are used then, in order to keep the curtains as near perpendicular to the envelope's surface as possible the cables must bifurcate and cross, as shown in Figure 7.8a for a four curtain system.

To prevent the crossing cables from rubbing together the curtains should be staggered; the curtains on one side of the airship being displaced forward a small amount, whilst the curtains on the opposite side are displaced an equal amount rearward.

Similar to a stretched line with a weight hanging from its mid point, the envelope cannot react to the vertical load in the curtain until it has deflected, forming a cusp as shown in Figure 7.8b. The resolved components of envelope tension in the opposite direction react the curtain's load. This is where the simile ends, because (unlike the stretched line) tension in the envelope does not rise as the deflection or load increases, since it does not have fixed end constraints. Tension in the envelope's membrane is determined by pressure vessel considerations, so it continues to deflect (with essentially constant envelope tension) making the cusp more acute until a balance is reached. In order to avoid deep furrows in the envelope's upper surface, the number of curtains should be increased as airship size is increased.

Connections at the envelope's lower surface primarily depend on:

- The gondola's sectional shape (see Figure 7.6).
- Relative vertical position (large gap, nested or inserted).
- Gondola suspended weight to length ratio, compared with the envelope's shear carrying capability.

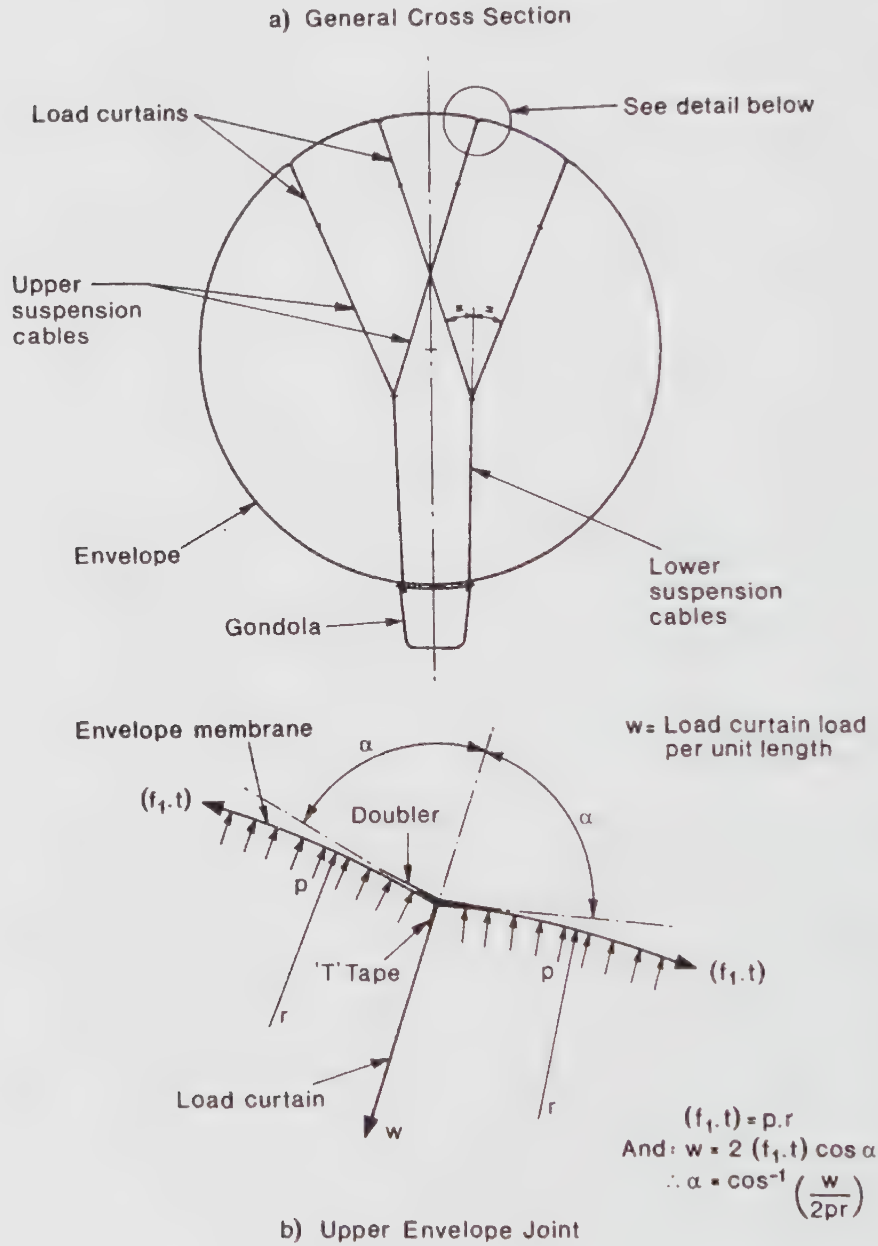

Figure 7.8. Four curtain suspension system arrangement.

If the gondola nests against the envelope with a small gap (2.5 to 10 cm) and its sidewalls extend up to the interface, then a simple shear collar may be all that is necessary. This is a strip of envelope material (about 20 cm wide) that wraps completely around the gondola, being attached continuously at its lower and upper edges to the gondola and envelope respectively. Whilst the collar has no effective shear stiffness, under load it buckles, allowing - provided its width is limited - a small movement at the interface until a diagonal tension field is set up (similar to a thin walled beam in bending), thus transferring the shear forces from the gondola to the envelope where they are reacted.

Provided the shear flow (load/unit length) is within acceptable limits for the envelope (approximately 10% of the tensile strength, if wrinkling is to be avoided), then no further connections are necessary. A short gondola, however, may be effectively lengthened using battens (similar to those of the nose group) attached at the gondola's extremities. In addition, a small portion of the shear collar at the front and back of the gondola helps to carry longitudinal loads by direct tension into the envelope. This only occurs at one end, where tension is created, since the opposite end goes slack.

If the gap is large or the gondola's shape does not permit a shear collar of small width, then movements at the interface may be unacceptably large for a shear collar alone. The gondola's motion beneath the envelope may be compared with that of a four bar chain. Special methods for the particular application may need to be devised, incorporating cables from finger patches on the envelope (arranged in martingale fashion, to brace the gondola) and lower envelope surface battens to transfer the load into the envelope. Rigging methods to pre-tension the arrangements will also be necessary.

In this application the shear collar may be more effective as a lower surface arched load curtain, supplementing the internal suspension system by carrying a proportion of the vertical suspended weight. It can then also act as a fillet fairing between the gondola and envelope, providing enhanced aerodynamic properties. In this respect the arches need to be closed by light weather-strips, which may be folded back to give access for maintenance purposes.

If the gondola is partially inserted via a large aperture into the lower envelope surface then shears may be fed directly through the interface connections with minimal deflections. The aperture in the lower envelope surface should be designed using similar principles as for an arched load curtain (discussed above), using a continuous bolt rope from which connections with the gondola are made. The attachment points may also be supplemented with finger patches, as necessary. The connecting members should be length adjustable for rigging purposes. The gondola should be used to carry envelope tensions (dependent on gas pressure) from one side of the aperture to the other. In addition a sealing membrane is required to close the gap between the arches and the gondola. Weather-strips may also be required, as for the external load curtain described above.

Whilst this last method may cause some consternation with respect to the size of the aperture in the envelope (as a pressure vessel), which adds to the complication when the envelope is inflated, it should not be dismissed when considering the airship's role. It has, after all, been done before, as evidenced by the US Navy's ZPG 3W airship (42500 cu m). Merits of this method are as follows:

- The large aperture may also be used to install large objects inside the envelope, such as mission antennae or additional fuel tanks.
- Installations in the envelope could be connected directly on the gondola, as a stable base, without the need for additional envelope penetrations.
- The myriad penetrations normally put in the envelope's lower surface above the gondola for: suspension cables, viewing, access, ballonet air supply system, through fittings, etc, would be obviated.
- Access into the envelope could be made safer and relatively simple, using a turret on top of the gondola with a sealing door and extra facilities for air supply. The turret could also be used to improve internal inspection.
- The airship's centre of gravity would be raised, improving handling qualities.
- Depending on overall layout of the propellers, overall airship height could be reduced, thus easing hangar entry.

Whichever method of support is adopted, fail-safe design principles should be applied. Cable failures within the envelope are not easy to detect (particularly when one considers: the airship's size, poor lighting conditions and difficult viewing facilities); it is essential that the system functions safely following such a failure.

Tail Group

The tail group normally comprises a set of fixed fins fitted with control surfaces from hinged brackets at the trailing edge. They are located at the airship's rear end to provide stability in flight and, by operation of the movable trailing surfaces, effect control - similar in principle to the empennage of other aircraft. The fins may be held in place by an external support system.

The fins' actual position along the hull must be determined from an optimisation exercise between various influences as follows:

- The further aft the greater the moment arm, enabling small surfaces to be used, but read on.
- The further aft the smaller the hull's diameter causing the surfaces to operate in poor air-flow behind the hull's bluff fore body, which also causes a deep turbulent boundary layer, requiring larger surfaces of greater aspect ratio to overcome the effects.

- The further aft the smaller the hull's diameter and therefore the smaller its aerodynamic influence, which contributes significantly to overall empennage loads, requiring larger surfaces to compensate.

- The further aft the smaller the hull's diameter and therefore the smaller the envelope's membrane tension and overall section, affecting its ability to support the fins, requiring a larger fin footprint, attachment fittings and possible stern reinforcement to spread the loads.

- The further aft the more effect overweight-fins will have, requiring larger counter balance weights to be added at the nose.

In addition to position, the number of tail surfaces (fin plus control surface), circumferential arrangement, aspect ratio, section profile and plan form must be determined. Having established these parameters the structural design of the units may be undertaken. An objective of the design should be to make all tail surface units structurally identical, to economise on their production.

If an arrangement (such as cruciform), with the lower surface on the longitudinal centre-line of symmetry, is selected the lower surface may have to be truncated to provide ground clearance for take-off and landing. It may also require a fender to protect it from impacts with the ground. The arrangement should be configured so that snow will not settle on them or can be removed easily. A typical tail surface arrangement is illustrated in Figure 7.9.

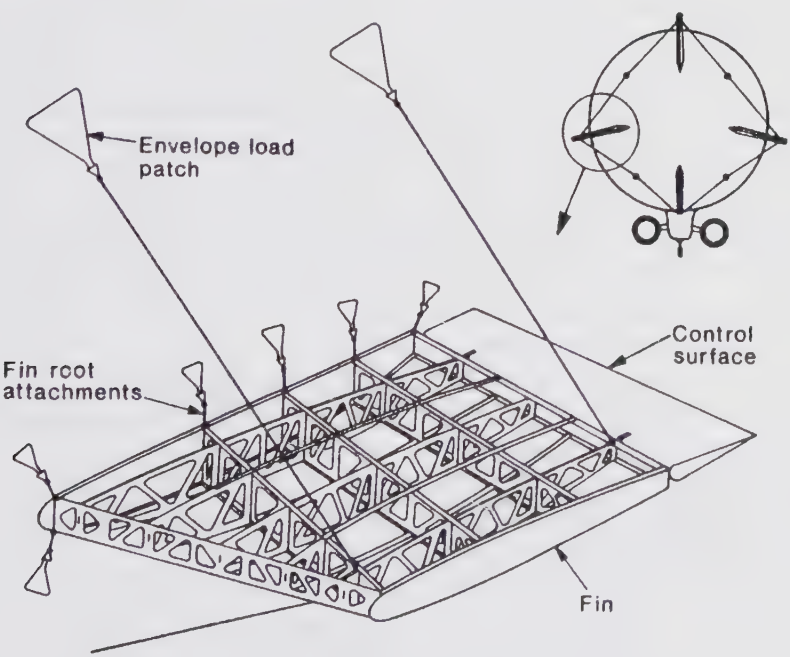

Figure 7.9. Tail surface structural arrangement.

The fin usually comprises a set of interlocked spars and ribs, sparsely arranged in lattice form to provide a stiff structure (similar to an egg box arrangement). As far as practical the arrangement should be squared to avoid complication. Depending on size, the fins may also need to be constructed from major sub-assemblies with joints that can be disassembled for transport purposes.

Most of the lattice structure may be skinned with doped heat shrink fabric to provide a smooth aerodynamic profile. A NACA 0008 series profile of 8% depth to chord ratio, with its maximum thickness at 30% chord length, has been used in the past. Internal cross bracing to hold the lattice arrangement may also be necessary. The skin's lower surface should also have small drain holes at positions where water may collect.

The leading edge should be stiffened against aerodynamic pressure and effects of abrasion. This may be achieved using lightweight thin gauged sheet material, to form a D shape, backed by a raked spar. Similar sheet material should also be used between the root rib and the first rib outboard, to stiffen this area against the reactions from the envelope as the fin is pressed into it. The root rib should be profiled to conform with the envelope's shape, be of smooth form and have generously curved edges and corners to prevent the envelope from being damaged.

Fittings to install the fin on the envelope should be provided at the root end (for shear attachments) and at outboard positions (for bracing cables). In addition, fittings to enable the fin to be lifted into position may be necessary and hinge brackets, extending rearwards from the fin's rear spar, are needed to carry the control surface.

The control surface may be like a barn door, hinged at its leading edge. Such an arrangement, however, would require large aerodynamic horns and powerful tabs to help reduce the hinge moments and/or be fitted with a powerful operation system (which may be heavy and slow to operate). In addition, the horizontally inclined surfaces might also need a substantial amount of mass balancing to prevent droop and/or employ spring balancing, which may affect the dynamic behaviour.

A more sophisticated solution is to provide control surfaces with hinges set back to a position just ahead of their aerodynamic and mass centres, at approximately 30% chord. If designed carefully tabs, aerodynamic horns, mass and spring balancing devices can all be obviated enabling a simple light weight solution with a low power but responsive operation system to be installed. The control surface's area is approximately 25% of the total tail surface area.

Another method that may be employed is to adjust the fin's profile so that it has a constant depth rear spar. A control surface of constant section, with hinge line parallel to the fin's rear spar, may then be configured. This enables the ribs to be of common construction, the spars to be of constant depth and the assembly to be a squared arrangement (easing and standardising the joints). For an airship the impact of such deviations on the aerodynamic performance is negligible.

Assuming control surfaces with set back hinges are selected, construction may be based on a central (roughly square) torque box comprising fore and aft spars closed with outer profile thin gauged sheet skins. Leading and trailing riblets can then be added, skinned with doped heat shrink fabric. The trailing edge will require a profiled edge strip over which to wrap the fabric and the leading edge may require thin gauged sheet skins to maintain the profile.

The control surfaces should be able to operate freely each way over an angle of approximately 25 degrees. Stops, however, should be incorporated at about 30 degrees to prevent runaway. The particular method of operation is largely dependent on size and role. In addition, a means to lock the control surfaces in their neutral position should be provided for maintenance. This may also be needed when the airship is moored, to prevent unwanted motions.

Conventional cable control systems have been used in the past. Whilst such methods are relatively cheap and simple, for a non-rigid airship the lost motion owing to flexibility and length may be substantial - reducing effectiveness and airship response. Also, the loads may be high and be coupled with large control movements, which place a heavy work load on the pilot, such that, in turbulent weather, the pilot's endurance may be severely reduced as a result of physical exhaustion.

Modern airships are now being fitted with remote control systems that incorporate mechanical actuators to operate the control surfaces. Such systems ensure that the degree of movement signalled by the pilot is applied at the control surface with negligible lost motion - improving control performance and airship response. It also reduces pilot work load, enabling long endurance flights with relative ease, and enables an autopilot system to be interlinked. Whichever system is adopted design of the control surfaces and their operating method, with respect to stiffness and inertia, must avoid flutter or structural resonances.

The tail surfaces may be guyed in place fairly simply using bracing cables, attached at outboard positions each side of the fin, which extend at approximately 45 degrees back to load patches on the envelope. A fail-safe system should be devised, since otherwise catastrophic failure (loss of the airship) could follow. A means to rig the cables (pretension them) is also needed. In addition, the fin should be tied to the envelope around the root rib to enable longitudinal and transverse shear loads to be restrained. This may be done using strong cord looped several times between finger patches on the envelope and fittings on the fin and then knotted. This method may require renewal at fixed intervals in the life of the airship.

Nose Structures

The bow of a non-rigid airship needs to be reinforced if:

- The envelope's internal pressure is not sufficient to stabilise the membrane against the aerodynamic pressure of flight, to prevent it from imploding. This is probable since otherwise the envelope's material would have to be stronger than necessary (hence heavier), to resist the inordinately high internal pressure.

- It is used to provide an attachment to a mooring mast.

- Handling/tow-in lines or a sea/ground anchor and associated winch equipment are to be fitted.

- It is used to install mass balance weights or ballast.

- It is used to mount a bow thruster.

Clearly, it makes sense to provide an all embracing structure optimised for the number of influences that must be covered. In its simplest form the nose reinforcing comprises an external set of identical members arranged in a regular pattern, like the spokes of a wheel, around the envelope's longitudinal centre-line. The members radiate from a central hub fitting, which may carry a mast attachment probe, following the envelope's profile and extending aft far enough for the envelope's pressure stabilised membrane to support the applied loads. Typically, this may be about 8% of the envelope's overall length. The stiffening members may be attached to the envelope by a simple pattern of lacing, using lengths of cord. The lacing arrangement should be devised so that it can resist longitudinal loads along the stiffening members, otherwise slippage may occur, as well as tying them to the envelope's surface.

In consideration of methods for handling the airship near the ground during the mooring phase a strong bow cap may be desirable to prevent the airship from being impaled on the mast owing to uncontrollable movements. This can also be used to carry additional ballast (disposable if desired), to balance the airship, or other appendages at the bow. It may take the form of a spoked wheel, when viewed from the front, formed to the shape of the bow, with the mast attachment probe at its centre. It can also be a simple cone, although this results in higher loads at its periphery - owing to the greater offset. To provide an aerodynamically smooth profile, it may be skinned using doped heat shrink fabric (easily repairable if necessary).

Typically, the size of the bow cap may be from about 10% to 15% of the envelope's overall diameter, designed to spread the mast reaction loads over a wide area. The bow cap should be held in position by:

- Lacing around its periphery, which primarily carry transverse shear forces - but also tie it to the envelope's surface.

- Longitudinal battens, which primarily carry longitudinal end loads.

The battens provide longitudinal continuity of the bow cap's spoked members and may be laced to the envelope in similar fashion to the longitudinal stiffening members discussed above. If the batten's attachment to the bow cap is a pin joint (allowing the joint to articulate as the envelope expands or contracts) then, in elevation, deformations owing to transverse mast reaction loads will be as shown in Figure 7.10.

As can be seen, the structure behaves in a manner similar to a four bar chain, putting compression into one side and tension on the other. At the same time the intermediate battens are displaced sideways which, owing to their shape around the envelope, introduces torsion to those members. For these reasons the battens should be of tubular form. It can also be seen that, on the compressive side, the lacing around the bow cap is put into tension by the action of the battens (trying to push the cap off) and the battens dig into the envelope at their aft end. The envelope may also buckle at this point. To prevent the battens from puncturing the envelope they should be of smooth form with splayed and rounded ends.

Under pure compression the envelope of a non-rigid airship may buckle at the end of its stiffening members. The load to do this is:

$$F = p.\pi.r^2 \tag{7.21}$$

Where:

p = envelope internal pressure.

r = envelope radius at the members aft end.

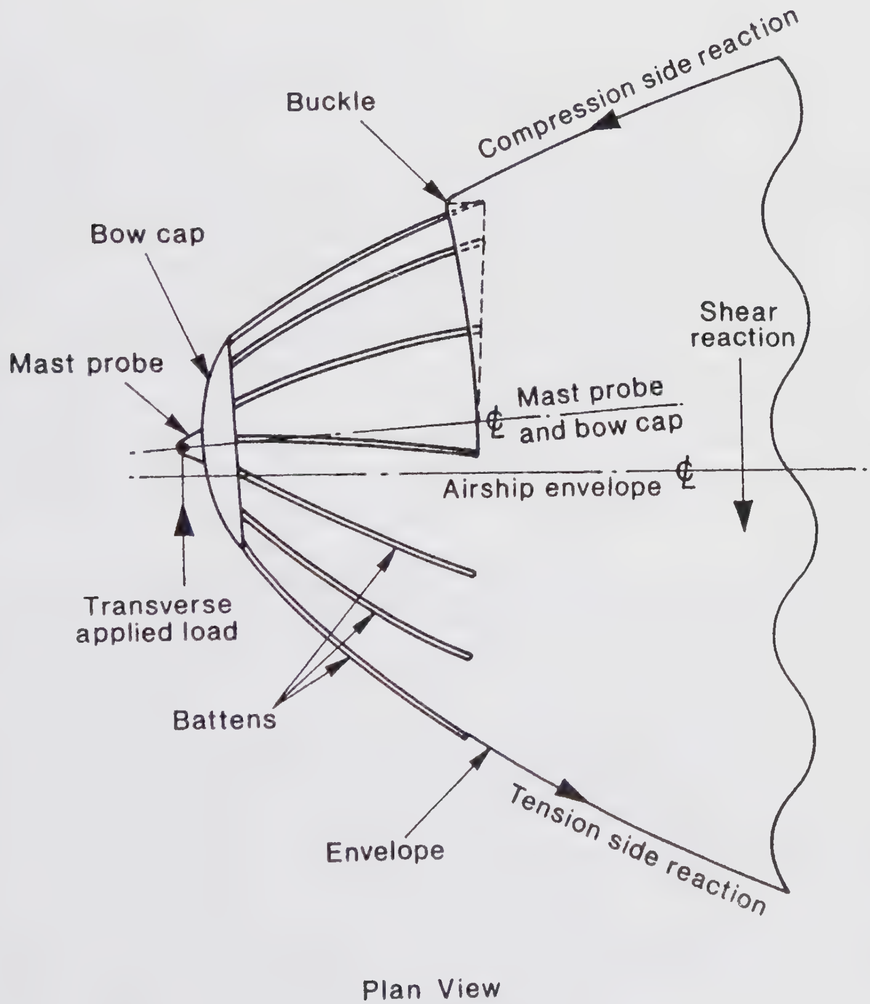

Figure 7.10. Deformed shape of bow stiffening.

Above this load the forward end structure merely pushes further into the envelope, like a piston in its sleeve, the load remaining essentially constant. When the load is removed the front end structure will simply pop back into shape without any apparent damage. This mechanism may be utilised in extreme conditions to cushion the mast loads, providing a means of energy absorption.

Analysis of the bow reinforcing structure, if tackled using finite element techniques, should ultimately employ large displacement and non-linear theory. This is necessary in order to model its behaviour correctly on a flexible fabric structure. In addition, tests should be performed to validate those parts of the model which, owing to the unpredictable behaviour, cannot be proved by other means. This should not be underestimated, since the assets of the airship company may hinge one stormy night on the single attachment point of the bow's stiffening structure to its mooring mast.

Landing Gear

The landing gear used by early airships was a bump bag or pontoon, similar to a boat's fender. Inflated with air this simple concept provided the necessary cushion against impacts arising from contact with the ground. Indeed, as a buoyant vehicle that floats in air, parallels for protection of the airframe and its handling in close proximity with the ground (as a ship to its pier) are appropriate. The pontoons also provided an excellent means enabling the airship to settle on water.

Landing, in fact may be an inappropriate term, since airships (similar to surface ships) remain essentially afloat - never really landing - even though they may be held in close proximity with the ground. Heavier-than-air craft on the other hand convert from being air borne when in flight to being ground borne when they land; their weight being transferred via the landing gear from the air to the ground. The landing gear more appropriately could be called a ground fender. These points are emphasised to help the reader understand essential design aspects and the nature of an airship's undercarriage.

The need for a wheeled undercarriage to reduce ground resistance arises from operational practices for take-off and landing with the airship in a state of static heaviness; requiring additional aerodynamic lift to become truly airborne. As a result, particularly if the airship does not have vectored thrust, a short rolling distance over the ground may be required, similar to that of an aeroplane, to gain sufficient air-speed for the aerodynamic lift to become effective. The reduction of ground resistance also helps ground handling and reduces the tendency to heel over as the airship moves sideways or weathercocks at the mast. Ground resistance may otherwise be considered useful in damping the airship's motion across the ground.

The number and position of the units depends on overall configuration of the airframe and propeller parts needing to be protected from ground impacts and to help maintain a horizontal attitude. One unit located approximately below the airship's centre of gravity is the minimum requirement, providing a least weight solution. The airship remains upright owing to buoyancy, but is inclined to pitch approximately +/- 8 degrees and roll about 12 degrees unless other restraints are applied.

If the airship does not have vectored thrust capability then, if statically heavy, it either requires a rolling take-off or may be bounced off the ground using the landing gear as a spring. In the second case a landing gear with no recoil damping may assist the take-off processes. For large airships the second method is not practical, since it requires a large ground crew. To prevent the airship from being pushed up from the ground in a bouncing mode when it lands recoil damping is necessary. The recoil rate needs to be compatible with the airship's bouncing mode frequency, otherwise the shock absorber may still be compressed when the airship returns to the ground.

Simplistically, the kinetic energy of descent to be absorbed by the landing gear is:

$$E = (M.v^2)/2 \tag{7.22}$$

Where:

M = Total Mass under consideration.

v = Vertical rate of descent.

For an airship with an underslung gondola supported by an external suspension system, with a wide gap between the envelope and gondola, M = mg.

Where: mg = Gondola suspended mass.

For an airship with closely coupled gondola and envelope, a much greater mass must be considered:

$$M = mg + mh + mi \tag{7.23}$$

Where:

mh = Hull mass (including: envelope, empennage, nose structure, etc, together with the ballonet air and lifting gas).

mi = Virtual inertia of the airship.

The extent to which these additional masses affect the design of the landing gear is dependent on the stiffness at the gondola's interface with the envelope and the stiffness of the envelope overall. The virtual inertia of an airship is a very significant term compared with heavier-than-air craft, since it can be greater than the mass of the airship itself. This term is largely applied via the envelope. The system to be analysed may be represented as shown in Figure 7.11.

A full dynamic analysis is needed to determine the maximum reaction accurately. A simplistic approach, however, which yields pessimistic results, is to assume the envelope is a rigid body rigidly attached to the gondola.

In addition to the kinetic energy the landing gear must also absorb the potential energy owing to maximum static heaviness:

$$PE = (w.z)/2 \tag{7.24}$$

Where:

w = Maximum Static Heaviness.

z = Total landing gear vertical displacement.

The work done in compressing the landing gear is:

$$W = (P.z)/2 \tag{7.25}$$

Where: P = Landing gear vertical reaction.

To determine the reaction we may equate the work done in compressing the landing gear with the kinetic and potential energy to be absorbed, hence:

$$(P.z)/2 = (M.v^2)/2 + (w.z)/2 \tag{7.26}$$

Therefore,

$$P = w + (M.v^2)/z \tag{7.27}$$

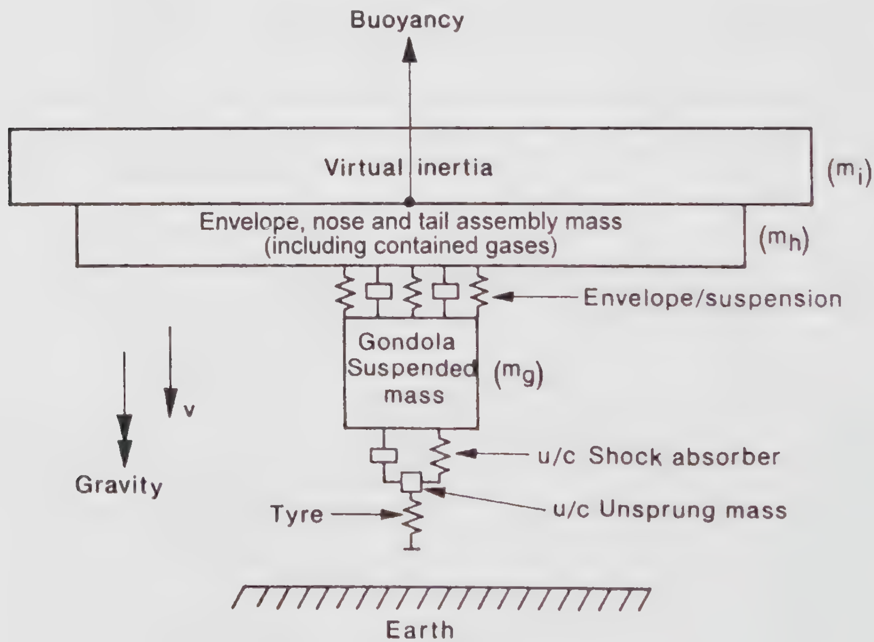

Figure 7.11. Dynamic simulation model.

The value of this reaction is very large compared with the maximum value for static heaviness. Maximum static heaviness is about 5% of the value for maximum gas lift: whereas the maximum reaction for a descent rate of, say, 5 ft/s (with the envelope treated as a rigid body rigidly connected to the envelope) is about 60% - which is the same order of magnitude as the gondola suspended weight - depending on vertical displacement. If the gondola can be isolated from the envelope the reaction would only be about 25%. Clearly the coupling between gondola and envelope is an important aspect that needs to be investigated.

With a reaction this large a single landing gear unit either needs to be fitted with a large balloon tyre or more wheels, to provide a footprint large enough for the ground to accommodate the load. Since the static load is very small, and may even be zero if the airship is in a state of neutral equilibrium or statically light, brakes would be ineffective if fitted. The wheel unit should be able to castor freely through 360 degrees to any position for ground handling and take-off purposes. After take-off the wheels need to be aligned so that they trail aft, to reduce drag and be prepared for landing. This requires an additional mechanism to be devised.

Compared with heavier-than-air craft the vertical displacement (tyre plus shock absorber) needs to be large to minimise the reaction load, with an element of viscous damping to increase efficiency by maintaining its peak value throughout the compressive stroke. This also enables the gas lift to play its part in arresting the envelope's descent as the gondola's load is transferred to the ground, the time of reaction being longer.

Obviously, descent rate (being a squared term in the above equation) needs to be kept as low as possible. The authorities stipulate a minimum value of 3 ft/s. This value was used for the SKS500 airship's original landing gear (designed in 1979 by Airship Industries), which, from personal knowledge, failed on numerous occasions - including those arising from bad weather conditions at the mast. Blakemore (1927) recommends a value of 8 ft/s, resulting in loads 7 times greater. This may have been thought necessary not just for free flight landing situations but to arrest uncontrolled kiting motions at the mast. Later work done by Airship Industries showed that vectored thrust procedures for control of the final descent may enable a lesser value to be adopted. They also found that, if the airship at its mast is kept in a state of static lightness, severe impacts are much less likely. In view of such procedures, a value of 5 ft/s may be appropriate for design. The actual value used needs to be established from trials and analysis simulating both free flight and mast mode situations.

Consideration of the pitching and weather vane type motions at the mast need to be given, otherwise the landing gear may be subjected to unnecessary loads. To accommodate the airship's motion as it circulates around the mast the wheels should be aligned athwartships and prevented from castoring. This, however, presents a problem each time contact with the ground is made. Figure 7.12a shows the airship's motion restrained at its nose by a mast. Clearly, the wheels do not move vertically, since the airship is constrained so that it can only move in a circular arc - rather they move toward and contact the ground at the angle of tangency shown in the Figure. As the tyres and shock absorber compress to absorb the energy of this motion the contact point moves forward, as shown in Figure 7.12b, dragging the wheels at 90 degrees to their fixed attitude. This scrubbing action puts a heavy load across the tyres, trying to prise them from the wheels, and, owing to trail and the locked position, introduces torque up the leg.

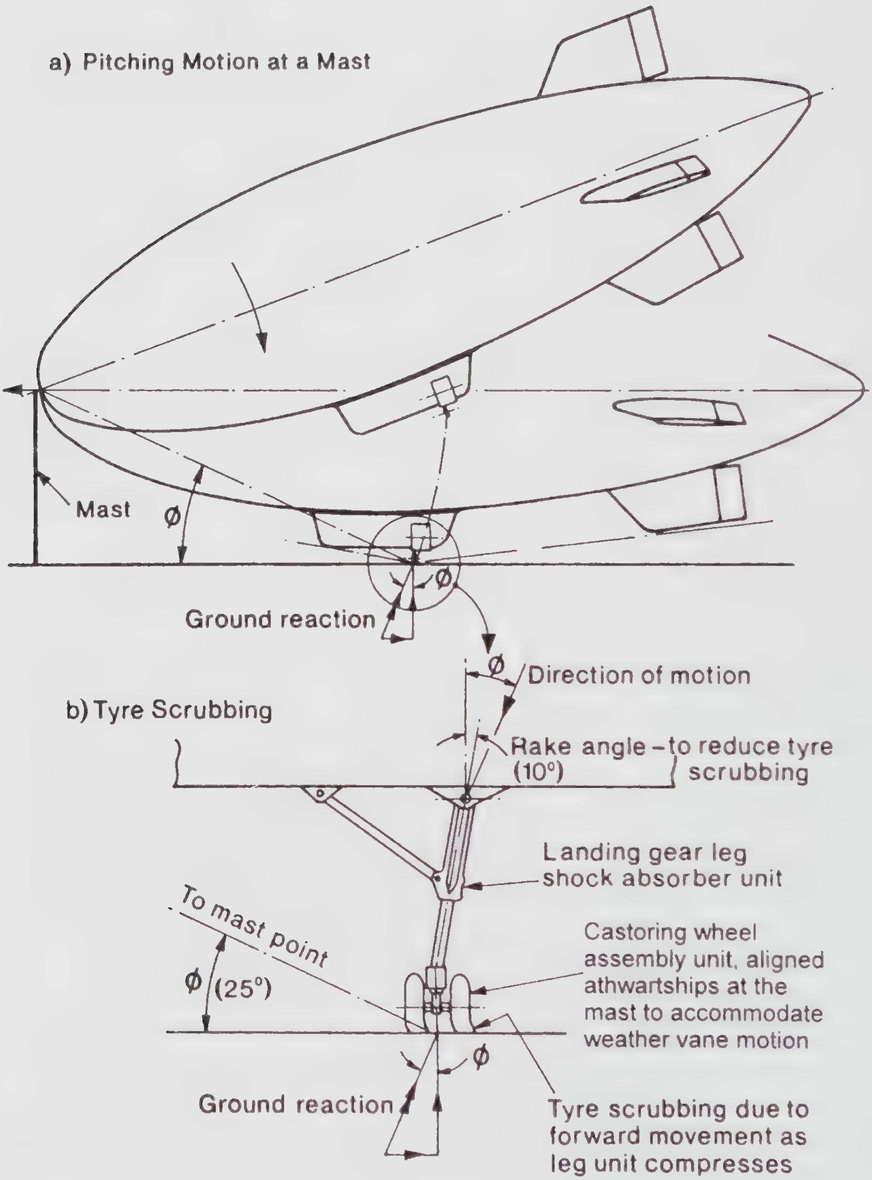

Figure 7.12. Vertical landing leg attitude.

If the leg is raked forward so that the shock absorber aligns with the angle of tangency then the scrubbing action may be minimised. This angle, however, may also be more than the ground reaction can accommodate; depending on overall airship configuration, this angle is about 20 degrees from vertical. When frictional resistance between the tyre and the ground is low (owing, say, to ice) the ground can only react vertically. The airship when free from the mast also lands normally with vertical movement. As a result, a leg with such a large forward rake would be subjected to high bending at its upper attachment and, owing to trail and the resolved components of the load, torque up the leg opposite to that caused by the scrubbing motion.

The solution is a compromise between the forces owing to the scrubbing action and the resultant loads of the raked leg, such that the torque is neutralised for normal conditions. A rake of about 10 degrees therefore needs to be introduced.

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8

Aerostatics

J. Craig

INTRODUCTION

This Chapter provides an appraisal of airship aerostatics with an emphasis on the mass properties aspects and on operational considerations. Chapter 2 has already covered the Basic Principles of aerostatics. Chapter 13 on Performance also covers some of the same subject matter. Apologies are given now for any repetition and also if this section tends towards over-simplification. The author considers it necessary that all those involved with airships have a good understanding of the basic principles. Hence the first few paragraphs are aimed at airship novices - though they might also help clarify some misunderstandings which seem to crop up from time to time amongst those who have been involved in the industry a lot longer.

This Chapter aims to give an understanding of why and how an airship can lift and to provide the means of calculating lifting performance. It also provides an awareness of many of the conditions that will affect the lift through all stages of the flight.

A full list of the abbreviations and notation used is given at the end of the Chapter. The main ones though are:

Lg	=	gross lift (kg)
Ln	=	net lift (kg)
T	=	temperature (°K unless otherwise stated)
M	=	total mass of gas (kg)
Ma	=	mass of ballonet air (kg)
Mg	=	mass of contained gas (kg)
p	=	pressure (N/m^2)
ρa	=	air density (kg/m^3)
ρg	=	contained gas density (kg/m^3)
ρn	=	net or lift density (kg/m^3) = $\rho a - \rho g$

the main subscripts used are;

$_0$	=	ISA, SL conditions
$_S$	=	Standard conditions (following temperature profile defined by ISA)
$_A$	=	Off-Standard conditions (same pressure but different temperature to ISA at same altitude)

THE ATMOSPHERE

An airship is dependent on the principles of buoyancy (see later) for its primary lift. The buoyancy is dependent on the density of the displaced fluid (along with the displaced volume) and, therefore, the properties of this fluid are of great concern. In the case of an airship, the fluid in which it operates is quite simply the atmosphere. The properties of the atmosphere, even in the relatively small region in which an airship operates, vary greatly. It is, therefore, extremely valuable - probably essential - for the understanding of the aerostatics of an airship to be aware of the changing properties of the atmosphere.

The next paragraphs will give such an understanding and explain the necessary steps to take in determining the atmospheric properties.

The atmosphere is a mixture of gases, primarily oxygen and nitrogen. For the range of altitudes involved in airship operations, in fact for conventional aerodynamics generally, the composition of the atmosphere varies only slightly and may, therefore, be regarded as a homogeneous gas. For the purpose of airship analysis, only the lower region of the atmosphere - the troposphere - will be considered. This covers altitudes up to 11,000 metres.

The International Standard Atmosphere (ISA)

The physical properties of the atmosphere vary greatly. For data - especially comparative data - based on the properties of the atmosphere, such as lift, it is important to have some sort of baseline or datum. This baseline is the International Standard Atmosphere (ISA). It was agreed to allow approximation of the atmospheric conditions prevailing for most of the year in temperate latitudes. The ISA is defined by the pressure and temperature at mean sea level and by the variation of **temperature** with altitude. From this variation in temperature, the other physical characteristics of the atmosphere (pressure, p and density, ρ) are derived. Data for Off-Standard atmospheric conditions can be produced by adding a constant temperature variation - which can be positive or negative - from the ISA. By definition, the pressure at a given altitude is constant for both Standard and Off-Standard atmospheres. The data presented in this section is given for S.I. units and care must be taken to ensure that these are consistently used.

ISA Mean Sea Level Conditions, (T_0, p_0, ρ_0)

The starting point for all ideal atmospheres derived from ISA is the ISA Sea Level (SL) condition. The temperature at ISA SL, T_0, is 288.15°K (15°C) - note all formulae used in deriving atmospheric properties use the Kelvin scale, °K, where 0°C = 273.15°K. The pressure at SL, p_0, is 101325 N/m^2 and the density of air, ρa_0, is 1.225 kg/m^3.

ISA Properties (T_s, p_s, ρ_s)

The density and pressure is dependent on the temperature at the required altitude. ISA defines a series of temperature gradients which cover the regions of the atmosphere. The concern here is with the lowest region, where ISA stipulates a linear temperature gradient of -0.0065°K per metre altitude (i.e. the temperature decreases by 0.0065°K for every metre climbed). Therefore, at ISA conditions, the temperature at a pressure height H_p (m) is given by :

$$T_s = 288.15 - 0.0065\ H_p \tag{8.1}$$

Therefore, at 1500m ISA the temperature T_s is 288.15 - 0.0065x1500 = 278.4 °K (5.25°C). The density at ISA varies exponentially with the temperature ratio, i.e.:

$$\rho_s = \rho_0 (T_s/T_0)^{4.3} \tag{8.2}$$

where the exponent 4.3 is an approximate value (see Equations 8.27-8.30). Therefore, at 1500m ISA, the density of the atmosphere is given by :

$$\rho a_s = 1.225\ (278.4/288.15)^{4.3} = 1.0565\ \text{kg/m}^3 \tag{8.3}$$

The pressure at ISA similarly varies with the temperature ratio, i.e.

$$p_s = p_0 (T_s/T_0)^{5.3} \tag{8.4}$$

where, the exponent 5.3 is also an approximate value (see Equations 8.27-8.30). Both pressure and density at any altitude in the ISA can be seen to be dependent on, and defined from, the temperature alone.

Off-Standard Atmospheres

An Off-Standard atmosphere is defined by a temperature difference from ISA. This temperature difference is constant for all altitudes.

Off-Standard Properties (T_A, ρ_A, p_A)

The pressure - by definition - is the same for Off-Standard and Standard atmospheres (e.g. the pressure at ISA 1500m is the same as ISA+15 1500m = 84428 N/m^2) . The density is dependent upon the ratio between Off-Standard and Standard conditions, i.e.:

$$\rho_A = \rho_S\left(\frac{T_S}{T_S + \Delta T}\right) \tag{8.5}$$

where ΔT is the difference between Standard and Off-Standard (i.e. for ISA+15 $\Delta T = 15$). For example, to derive the density at ISA-5, 1200m, the ISA conditions at 1200m are:

$$\left|\begin{array}{l} T_S = 288{,}15 - 0{,}0065 * 1200 = 280{,}35^\circ K(7{,}2^\circ C) \\ p_S = 101325\left(\dfrac{280{,}35}{288{,}15}\right)^{5,3} = 87609\ N/m^2 \\ \rho a_S = 1{,}225\left(\dfrac{280{,}35}{288{,}15}\right)^{4,3} = 1{,}089\ N/m^3 \end{array}\right| \tag{8.6}$$

and at ISA-5, 1200m the conditions are:

$$\left|\begin{array}{l} \Delta T = -5 \\ T_A = 280{,}35 - 5 = 275{,}35^\circ K(2{,}2^\circ C) \\ p_A = p_S = 87609\ N/m^2 \\ \rho a_A = \rho a_S\left(\dfrac{280{,}35}{275{,}35}\right) = 1{,}089\left(\dfrac{280{,}35}{275{,}35}\right) = 1{,}109\ kg/m^3 \end{array}\right| \tag{8.7}$$

Relative Density, σ

The relative density is the ratio of the density at the required conditions, ρ_a, to the density at ISA SL, ρ_0.

$$\sigma = \frac{\rho_A}{\rho_0} \tag{8.8}$$

Values of σ for a range of Off-Standard conditions have been plotted against altitude in Figure 8. 1.

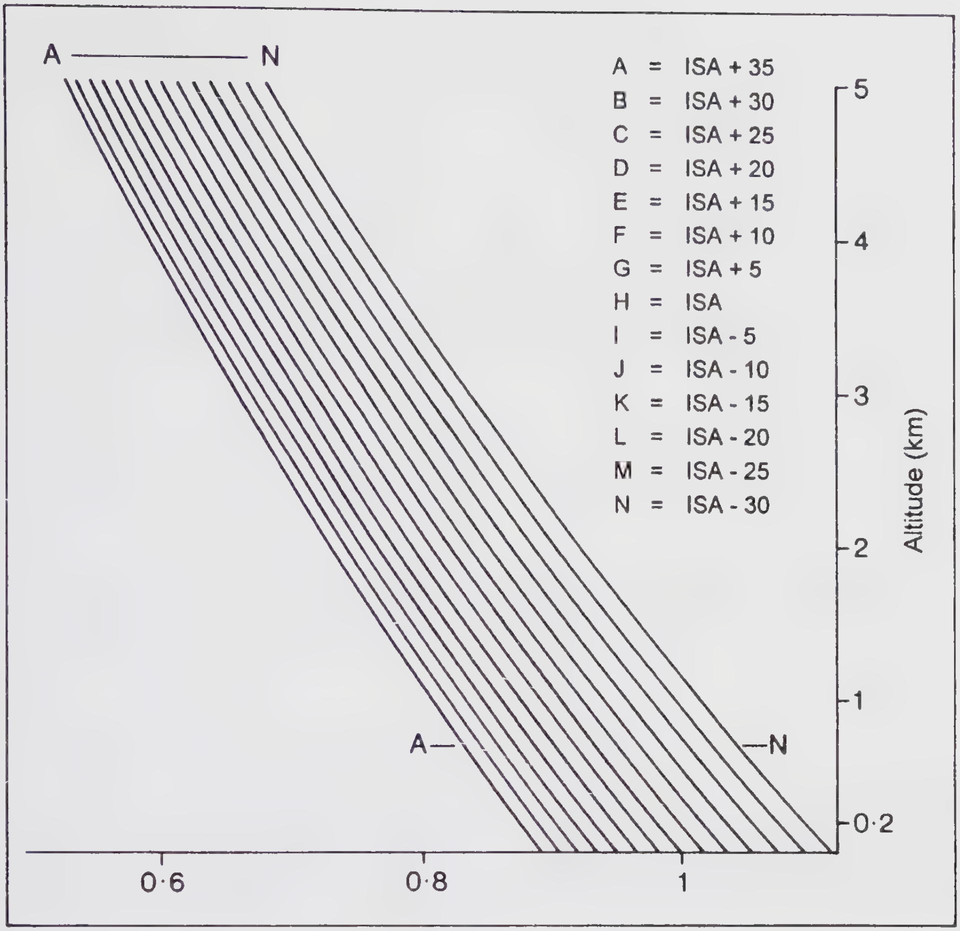


Figure 8.1. Relative density, σ, for a range of Off-Standard conditions against altitude.

CONTAINED GAS

The gas contained within the envelope, often called the lifting gas, will also change in the same way as the atmosphere and the same calculations apply.

For the purpose of this text, the contained gas is assumed to be helium. It is extremely unlikely that the gas will be 100% pure, but will contain impurities in the form of air. Due to the porosity of the envelope fabric, and also due to some leakage in the fittings, the purity will decrease during operation - and it is well to keep this in mind.

To calculate the density of impure helium at ISA SL use the following formulae:

$$\rho g = (k \times 0.169 + (1 - k) \times 1.225) \tag{8.9}$$

where 1.225 is the ISA SL density of air; 0.169 is the density of 100% pure helium at ISA SL (both figures in kg/m3); and k is percentage pure helium (e.g. if helium is 97% pure then $k = 0.97$). Simply calculate the density of the helium at altitude in both Standard and Off-Standard conditions by multiplying the ISA SL value by the relevant relative density.

The contained gas is, however, subject to additional conditions. Firstly, it is at a higher pressure than the ambient atmosphere. This has a small effect but because it is constant, or relatively so, it can be generally ignored. Another change which cannot be ignored is superheat. This is where the contained gas is at a different temperature from the surrounding air. Not only can this have a significant effect but it can also vary throughout a single flight. Both these conditions are addressed in more detail later in this Chapter

BUOYANCY & STATIC LIFT

There are several terms which are used extensively in aerostatics. The following are brief explanations of these terms.

Buoyancy, *B*

Buoyancy is a force which is equal to the weight of fluid which a partially or completely submerged body displaces. The force acts in opposition to the weight, i.e vertically upwards. The term buoyancy is used primarily in hydrostatics, whilst in aerostatics the term static lift is almost exclusively used in its place. For consistency, static lift will be used rather than buoyancy throughout the remainder of this Chapter.

Gross Static Lift, *Lg*

The gross static lift is the true equivalent of the term buoyancy and is equal to the weight of the air displaced by the envelope volume;

$$Lg = Vn.\rho a \tag{8.10}$$

The envelope volume could be either gross 'Vg' (i.e. the total volume of the envelope including ballonets) or net 'Vn' (i.e. the envelope volume excluding ballonet volume). Which volume is used is dependent on how the envelope/gas system is viewed - i.e. as an open or closed system (explained later in this Chapter).

Net Static Lift, *Ln*

The net static lift is the gross static lift less the weight of the contained gases within the gross envelope volume. Again this varies according to how the system is viewed:

$$Ln = Lg - M = Vn.\rho n \tag{8.11}$$

where:

$$\rho n = \rho a - \rho g \tag{8.12}$$

This net density, ρn, is often called the lift density.

Centre Of Buoyancy (*CB*)

The centre of buoyancy is the centre of gravity of the displaced fluid. It is the point through which the static lift acts.

Centre Of Gravity (*CG*)

The centre of gravity is the point through which the weight of an object can be taken as acting.

Static Heaviness (*SH*)

The static heaviness is the amount by which the weight of the airship system exceeds the net static lift. The airship system comprises the airship vehicle and its systems, all the fluids (fuel, oil, water ballast etc.), the crew and payload (whether cargo, equipment or passengers) and ballast.

$$SH = W_{airship} - Ln \tag{8.13}$$

If the airship system weight is equal to the net static lift, then it is said to be in equilibrium (eq.). The vehicle could also be statically light (or have a negative heaviness) if the net lift exceeds the airship weight. It is generally preferred for the airship to be heavy for control purposes, but it is also usually a requirement for the airship to quickly attain, or get near to, eq. in the case of an emergency. This is normally done by dumping water ballast or in extreme cases venting the lifting gas.

Airship Pressure Height

Care must be taken not to confuse airship pressure height with atmospheric pressure height, H_p The airship pressure height is the height at which the ballonets are fully deflated and is therefore the maximum height to which the airship can climb without over-pressurising the envelope or venting gas.

SUMMARY OF AIRSHIP OPERATIONS

An airship is dependent simply on the principles of buoyancy for most of its lift. Some is supplied aerodynamically with forward speed and/or vectored thrust, but this is generally used to offset heaviness. The buoyancy is dependent upon the density of the displaced fluid, and the density of this fluid (the atmosphere) varies greatly. The following will, therefore, examine how this variation in density affects the airship, or rather how the airship copes with the changes. As already mentioned, this section will address only the basic principles and will assume primarily ISA conditions. The many other factors affecting the lifting performance will, however, be addressed later.

It is explained earlier that, as an airship rises, the temperature and pressure change. Considering the contained gas, it can be seen from the Gas Law,

$$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2} \quad \text{or} \quad \frac{p_1}{p_2} = \frac{T_1}{T_2} * \frac{V_2}{V_1} \quad \text{or} \quad \frac{V_1}{V_2} = \frac{T_1}{T_2} * \frac{p_2}{p_1} \tag{8.14}$$

that, if the temperature and pressure change, the volume will somehow have to alter. If the volume cannot change, then the pressure of the contained gas will either increase, if the temperature increases, or decrease.

For most non-rigid and semi-rigid airships the differential between internal and external pressure must be kept to a fairly narrow range of values. Changes beyond these acceptable values could result in either unacceptable stresses being placed on the envelope structure (if the pressure difference is too great) or the envelope losing its structural integrity (pressure differential too low).

There obviously needs to be some method for allowing this change in density, and therefore volume, without detrimentally affecting the pressure. Ballonets provide this facility. These are basically separate volumes of air within the envelope which are effectively open to atmosphere. As the density of the contained gas increases, thus decreasing the volume required, air is forced into the ballonets maintaining the pressure differential. Similarly as the density decreases, air is pushed out of the ballonets as the volume required increases.

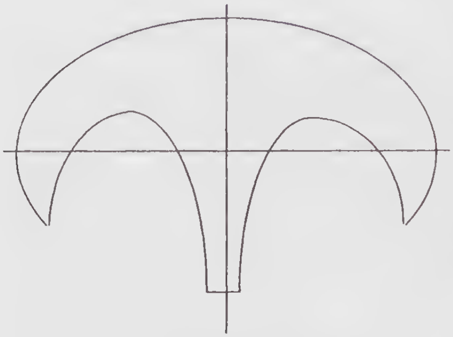
Consider the airship at the start of a particular operation as shown in Figure 8.2. The airship will have a certain amount of lift. This value can be calculated and measured - to some extent approximately. The gross lift of the airship at this point is the gross envelope volume (i.e. the volume occupied by the contained or lifting gas) times the density of the surrounding air at that time. The net lift (i.e. the lift available for the airship, its systems and payload) is the gross lift less the weight of the contained gas, and is equal to the net volume times the net density as shown in Equation 8.15. The net density being the difference between the air and the gas densities.

As the airship ascends (Figure 8.2b), the contained gases will try to expand. If they cannot expand then, as can be seen from the Gas Law above, the internal pressure - and therefore the pressure differential - will increase jeopardising structural integrity. In order for the volume of the contained gas to expand, air must be expelled from the ballonets. This means that the net volume, Vn, changes. As the mass of gas does not change (i.e. assuming none has leaked or been vented to atmosphere), the new volume required by the contained gas can be determined. It can be seen from the Equation 8.16 that the lift, both gross and net, does not change at any stage unless the contained gas escapes.

This situation (i.e. ballonets deflating as the airship rises) continues until the airship pressure height is reached (Figure 8.2c). At this point, the contained gas has expanded to completely fill the gross envelope volume, and the ballonets are flat. Lift is still the same as at any other point during the ascent. If, however, the airship continues to rise beyond its pressure height, the contained gas cannot expand any further and so either the pressure differential increases or gas has to be vented. As already mentioned some LTA vehicles are designed for higher pressure differentials to allow for this to happen. The vast majority, though, have valves fitted to allow gas to be vented keeping the envelope pressure within limits. As the airship rises beyond its pressure height, the density of the displaced air continues to decrease. The displaced volume, however, has now reached its limit and cannot increase any further. The gross lift, $Vn.\rho a$, must decrease. In order to maintain the pressure differential within safe limits, the contained gas will be vented as the airship rises. Therefore the mass of contained gas decreases.

As the lift has now decreased, the airship in effect becomes heavier. As the airship then descends, the volume required to contain this smaller amount of gas is obviously less than during the ascent and a greater amount of ballonet fill will be required at each equivalent pressure height. Therefore, one concern of exceeding the airship pressure height is that there will be enough ballonet volume left at ground level, i.e. the ballonets will not become 100% full before the airship reaches ground.

The foregoing discussion is based on the airship operating in ISA conditions.



(a) - 'Initial' Condition

Gross lift (buoyancy) = displaced volume x fluid density so:

$$Lg = Vn.\rho a$$

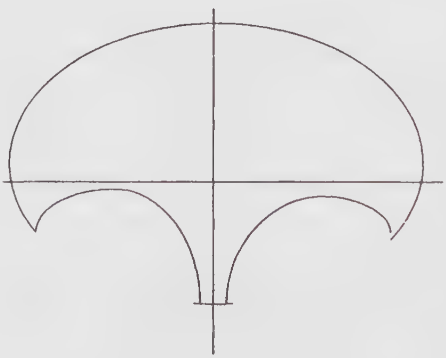
where $Vn = Vg - Va$

The net lift is the gross lift less the weight of the contained gases

$$Ln = Lg - M$$

where $M = Mg = Vn.\rho g$

$$Ln = Vn.\rho a - Vn.\rho g = Vn.(\rho a - \rho g) = Vn.\rho n \tag{8.15}$$



(b) - Airship Ascending

Gas expands. As the mass of gas remains constant, i.e. no gas is vented

$$Lg = Vn_S.\rho a_S$$

where

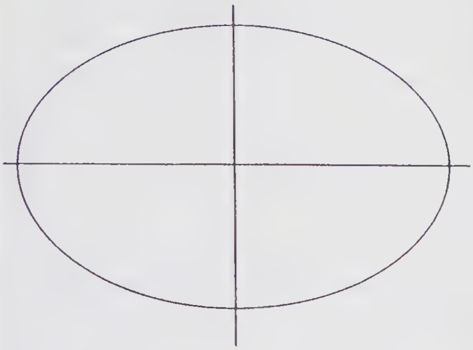
$$Vn_S = \frac{M}{\rho g_S} \quad and \quad \rho g_S = \sigma \rho g_0,$$

$$Lg = \frac{M}{\sigma \rho g_0}.\sigma \rho a_0 = M\frac{\rho a_0}{\rho g_0}$$

$$Ln = Lg - M = M\left(\frac{\rho a_0}{\rho g_0} - 1\right) = \frac{M}{\rho g_0}\rho n_0$$

$$Ln = Vn.\rho n \tag{8.16}$$

Figure 8.2a-b. Aerostatic parameters as airship ascends from 'initial' condition to pressure height.



(c) - Airship Pressure Height

At pressure height $Vn = Vg$ and net lift is still $Ln = Vn.\rho n$

Giving subscript $_1$ for conditions at pressure height and $_2$ for point beyond;

$$Lg_2 = Vg.\rho a_2 = Vg.\sigma_2.\rho a_0$$
$$Lg_1 = Vg.\rho a_1 = Vg.\sigma_1.\rho a_0$$
$$So \quad \Delta Lg = Lg_2 - Lg_1 = Vg.\rho a_0.(\sigma_2 - \sigma_1)$$

$$Ln_2 = Lg_2 - M_2 \;, \;\; M_2 = Vg.\rho g_2 = Vg.\sigma_2.\rho g_0$$
$$Ln_1 = Lg_1 - M_1 \;, \;\; M_1 = Vg.\rho g_1 = Vg.\sigma_1.\rho g_0$$
$$\Delta Ln = Ln_2 - Ln_1 = Lg_2 - Lg_1 - (M_2 - M_1)$$
$$\Delta Ln = Vg.\rho a_0.(\sigma_2 - \sigma_1) - Vg.\rho g_0.(\sigma_2 - \sigma_1)$$
$$\Delta Ln = Vg.\rho n_0(\sigma_2 - \sigma_1)$$

$$Lg = Vn.\rho a_S$$
$$Ln = Lg - Mg_S = Vn.\rho a_S - Vn.\rho a_S = Vn.\rho n_S \tag{8.17}$$

Figure 8.2c. Aerostatic parameters as airship ascends from 'initial' condition to pressure height.

OTHER FACTORS AFFECTING LIFT

The preceding explanation of the operation of an airship was extremely simplistic. There are many factors affecting the lifting performance and its determination. These factors can be split into two groups. Firstly, there are the variables resulting from inaccuracies in measurement of parameters such as ballonet volume, gross envelope volume, internal gas temperature and pressure. The effects of these errors will be briefly discussed. The second group of variables is related to weather effects and local variations in atmosphere.

Internal Pressure

The illustrations and calculations up till now have ignored the internal pressure differential, i.e. the fact that the internal pressure is higher than the ambient. Assuming the pressure differential is 2in WG, the effect on the density of the contained gas is to increase it by 0.5% at SL to just over 0.7% at 3000m. This is effectively negligible and, although it needs to be kept in mind, there is no need to allow for it in calculations.

Superheat

Superheat is an effect where the temperature inside the envelope is higher than the ambient air temperature. This is usually due to a greenhouse type of heating effect. Superheat causes the density of the helium to decrease. This increases its volume and thereby reduces the ballonet volume and weight of contained air. As the weight of helium is constant, the total gas weight decreases, and because the net lift is the gross lift less the total gas weight, there is an **apparent** increase in net lift. As the ballonet fill decreases under superheat, this apparent increase in lift is accompanied by an apparent decrease in airship pressure height. Superheat usually occurs when the airship is on the mast and in sunlight, etc. It will reduce or disappear as the airship starts flying. As it reduces the opposite effect happens, i.e. the net lift reduces and the weight of the airship, or rather its heaviness, increases. For this reason it is important that great care is taken to ensure the effects of superheat are accounted for at all stages of a flight. Negative superheat (i.e. where the helium temperature is lower than the ambient temperature) can occur but usually not to the same extent.

Weather Effects

Excluding superheat, which may be considered a weather effect, the main consideration would be in rain, snow or icing conditions. On the ground any rain, snow or ice on the envelope will add to the weight of the airship vehicle, reducing its payload. As an example, on a relatively small airship of 6500 m^3 volume a snow covering of 1/10 of an inch over 1/7th of its surface area will weigh over 100kg! Therefore, as much as possible should be removed prior to flight. If it is known that the proposed flight will encounter any of these conditions, then an allowance should be made. Due to the large surface area and relatively low speeds, a substantial amount of water, etc. may be collected thus increasing the heaviness of the airship.

Humidity

The effect of increasing humidity is to decrease the density of the air. This results in a reduction of the displaced mass and, therefore, the gross lift. This effect from humidity is worse the higher the temperature.

CLOSED OR OPEN

Throughout this Chapter so far, the envelope is considered as an open system, i.e the ballonets are open to atmosphere and are not considered part of the envelope volume. There is an alternative method of analysing the airship and its aerostatics, the closed system. In the closed system, the envelope is considered as a closed volume and the ballonets as separate bags within the envelope with a variable mass. Both systems produce identical results and both have their own advantages.

Figure 8.3 shows and compares the two systems. It can be seen that they give the same answer when used to derive net lift (Equations 8.18 and 8.19). The formula for the closed system continues to show that the mass of gas contained in the envelope (i.e. the mass of contained gas plus the mass of the ballonet air) can be expressed as the gross envelope volume times the contained gas density plus the ballonet volume times the **net** density (ρa - ρg) (Equation 8.20). This will be useful later. For simple lift calculations it is simpler to use the open system. When looking at airship trimming, however, it is more convenient to use the closed system.

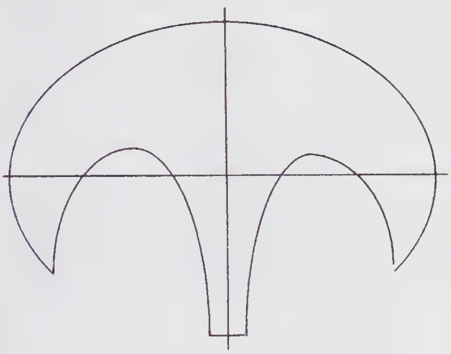
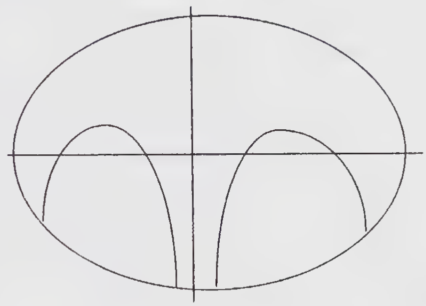
OPEN	CLOSED
	
$Lg = Vn.\rho a$ $Ln = Lg - M$ but $M = Mg$ $M = Vn.\rho g$ $$Ln = Vn.\rho a - Vn.\rho g$$ (8.18) $$Ln = Vn.\rho n$$ where $\rho n = \rho a - \rho g$	$Lg = Vg.\rho a$ $Ln = Lg - M$ $M = Mg + Ma$ but $M = Vn.\rho g + Va.\rho a$ $M = Vn.\rho g + (Vg - Vn).\rho a$ $M = Vn.(\rho g - \rho a) + Vg.\rho a$ $$Ln = Vg.\rho a - Vn(\rho g - \rho a) - Vg.\rho a$$ $$Ln = Vn(\rho a - \rho g)$$ $$Ln = Vn.\rho n$$ (8.19) note M can also be expressed as ; $M = Mg + Ma$ $M = Vg.\rho g + Va.\rho n$ (8.20)

Figure 8.3. Open and closed systems compared.

AIRSHIP BALANCE

The basics of aerostatics and its application to airships have so far been considered. It is almost equally important to be aware of the balance or trim of the airship. As for all types of aircraft, whether fixed or rotary wing, it is vital that the centre of gravity (*cg*) be within a prescribed range from some datum. If the *cg* is outside that range, it could lead to the aircraft becoming unstable or uncontrollable with predictably disastrous results. For airships, it is the relationship between the *cg* and centre of buoyancy (*cb*) which is the important parameter (knowing the position of the *cg* is valueless if the *cb* location is not known or specified).

For the airship to remain statically level (aerodynamic and thrust effects are ignored here), the *cg* should be directly below the *cb*. Any horizontal offset will result in the airship adopting a pitch angle (Figure 8.4). Theoretically this angle is the angle that the line passing through both *cg* and *cb* makes with the vertical The vertical separation between *cg* and *cb* affects the handling characteristics of the airship - the greater the separation the more stable the airship becomes, though greater control inputs are required for roll and pitch manoeuvres. The vertical relationship between *cg* and *cb* also affects the acceptable horizontal separation through simple trigonometry as is shown in Figure 8.5 (i.e. for an acceptable pitch angle α the further the *cg* is below the *cb* the greater the horizontal range can be). This is important to remember when quoting *cg* ranges.

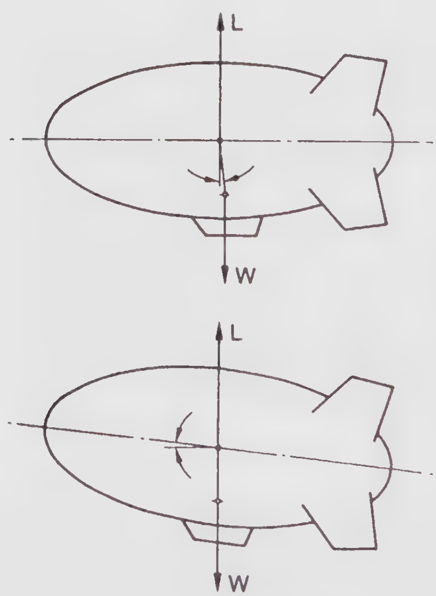


Figure 8.4. Influence of horizontal offset of *cg* and *cb*.

During the design phase much effort should be spent ensuring that the *cg* is as close as possible to the optimum position when considering the loaded airship. It would be, however, extremely unusual if the *cg* actually ended up where required through many factors. Added to the fact that the airship is likely to have to accommodate payloads of a wide variety - some of which will result in a *cg* position substantially different from the design typical - it becomes clear that there should be the facility to trim or change the *cg* - *cb* position. The airship should be loaded and ballast positioned to get the *cg* as close to the *cb* as possible. This is done using some sort of weight and balance schedule and loadsheet (see Chapter 9). It is extremely likely, however, that there will still be some trimming required to get the airship level and this can be done using the ballonets.

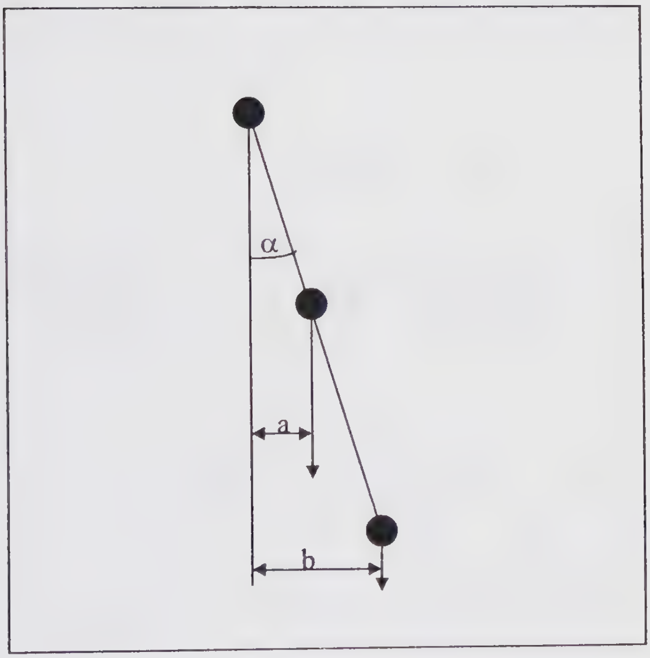


Figure 8.5. The vertical relationship between *cg* and *cb*.

We now can accept (hopefully) that the static trim of the airship depends on the *cg* - *cb* relationship. We will now, with the help of Figure 8.6 - which considers the airship as a closed system - look at the components of the moment unbalance of the airship. The figures in the left column show the airship with effectively equal ballonet fills. Initially, this condition will be considered. The top figure is the gross lift, which acts through the *cb*. The remaining three figures in the column make up the total weight which is 'balanced' against the gross lift. The resulting moments of the weights about the *cb* have to be calculated. It can be clearly seen that, irrespective of ballonet fill, the *cb* position is fixed (compare left and right hand columns of Figure 8.6). It can, therefore, be used as a datum from which to measure the weight moments. From the second figure it can be seen that the *cg* of the contained gas, irrespective of ballonet fill, is coincident with the *cb* and so the contained gas has a zero moment about the *cb*. This now simplifies the procedure considerably, as it leaves only the moments resulting from the weight of the ballonet air and those of the airship vehicle and payload which can be balanced out.

Now, if the airship is balanced, then the moment resulting from the ballonet air offsets the moment of the airship, i.e.:

$$\begin{aligned} &Wa.xa = -Ws.xs \\ &Wa_1.xa_1 + Wa_2.xa_2 = -Ws.xs \end{aligned} \tag{8.21}$$

However if they are not equal then a mass from the front ballonet can be transferred to the rear or vice versa, i.e air can be transferred forward or aft so:

$$\begin{aligned} &(Wa_1 + \Delta W).xa_1 + (Wa_2 - \Delta W).xa_2 = -Ws.xs \\ &Wa_1.xa_1 + Wa_2.xa_2 - \Delta W(xa_1 - xa_2) = -Ws.xs \end{aligned} \tag{8.22}$$

There are many benefits in having fore and aft ballonets both equi-sized and equi-spaced about the *cb*. If they are not, then the resulting moment could change significantly as the ballonet fill changes. If, therefore, it is assumed that they are, then:

$$\begin{aligned} &\mathrm{xa}_1 = -\mathrm{xa}_2 \text{ (see Note 1)} \\ &\mathrm{Wa}_1 = \mathrm{Wa}_2 \qquad \text{so} \\ &\mathrm{Wa}_1.\mathrm{xa}_1 + \mathrm{Wa}_1.(-\mathrm{xa}_1) - \Delta\mathrm{W}(\mathrm{xa}_1 - (-\mathrm{xa}_1)) = -\mathrm{Ws.xs} \\ &2\Delta\mathrm{W.xa}_1 = \mathrm{Ws.xs} \\ &\Delta\mathrm{W} = \frac{\mathrm{Ws.xs}}{2\mathrm{xa}_1} = \Delta\mathrm{V}.\rho\mathrm{n} \text{ (see Note 2)} \end{aligned} \tag{8.23}$$

Note 1. as cb is datum, one must be +ve and the other -ve.

Note 2. ρn and not ra - see Figure 8.3, Equation 8.20.

It is, therefore, possible to use the ballonets as a fine trim within realistic limits. It must be noted that, as the airship rises, the net density decreases and, unless the differential volume ΔV is increased, the moment will decrease resulting in the airship not being statically trimmed. This condition is worsened as the stage is reached where one ballonet is flat. Beyond that point, not only does the net density reduce but ΔV also reduces.

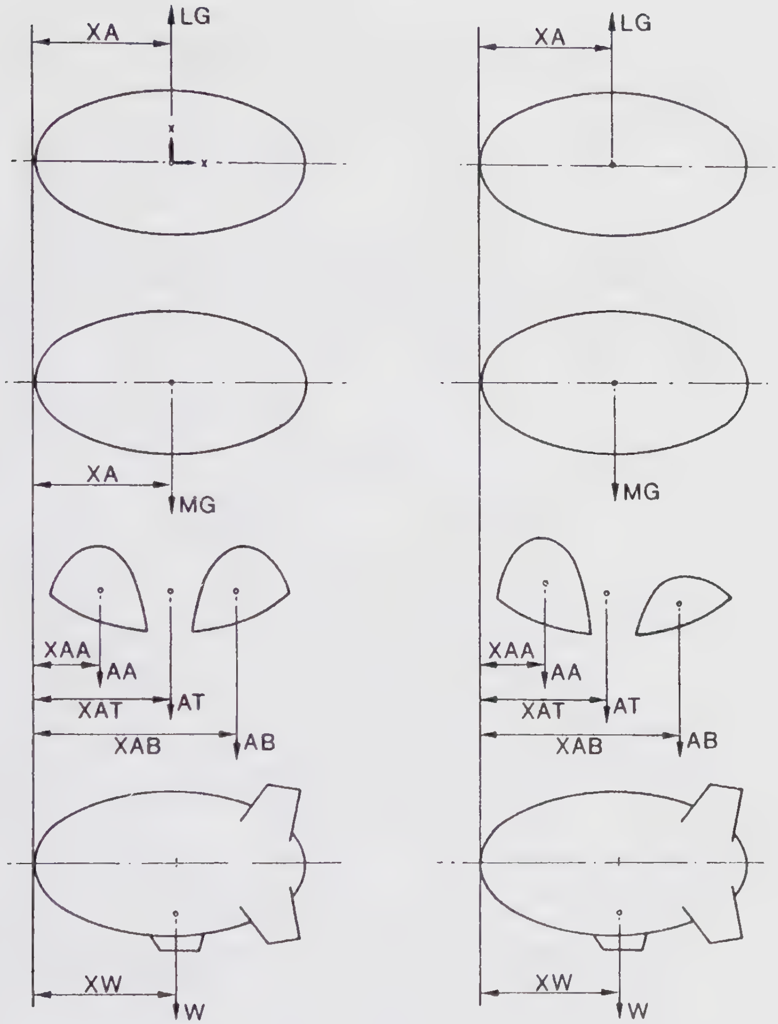


Figure 8.6. Moments in a Closed System.

Figure 8.6 showed the closed system and Figure 8.7 looks at the problem as an open system. Initially, it may appear simpler because there is one less component - the ballonet air. If left and right hand figures are compared, however, it can be seen that now the *cb* does not remain in a constant position for differential ballonet fills. This means the *cb* position has to be recalculated and the moments taken about the new position. Not only is this more difficult to visualise, but there is a greater chance of errors creeping in to the calculations.

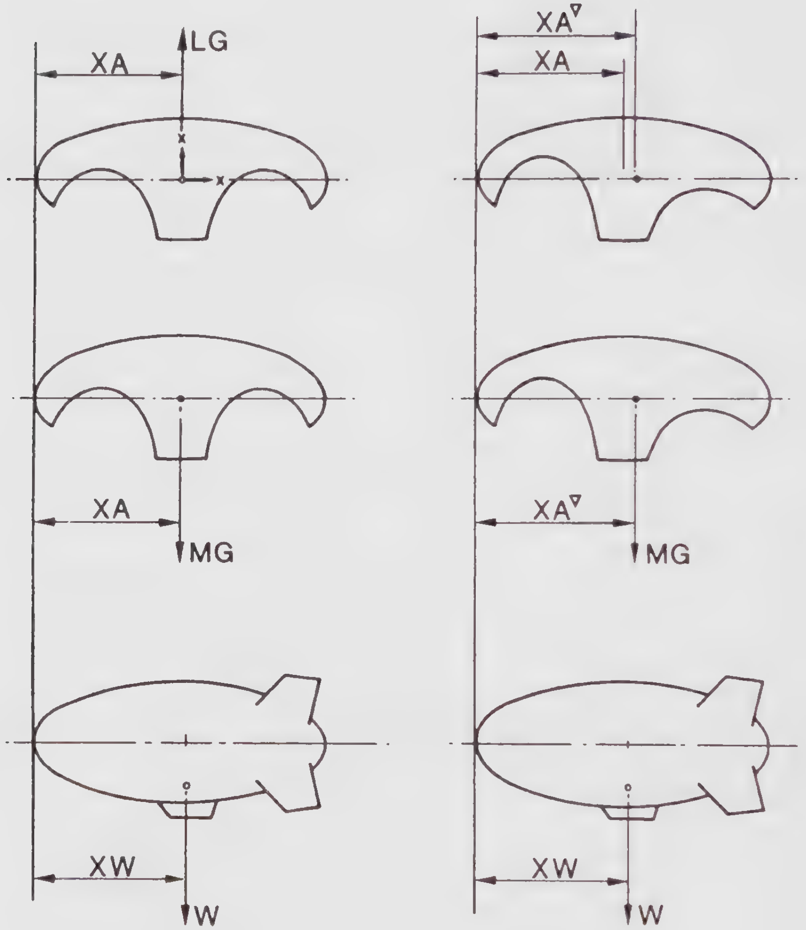


Figure 8.7. Moments in an Open System.

DERIVATION OF GAS MASS PROPERTIES

Introduction

A brief description of the atmosphere used in these calculations is given earlier in this Chapter. This section outlines the derivation used to obtain accurate densities for the atmosphere in Standard and Off-Standard conditions, and also for the contained gases within the envelope. The calculations are concerned only with the first part of the atmosphere, i.e. to an altitude of 11,000m. The air is assumed to be static (with respect to the earth), to be a perfect gas and to be free from moisture.

To keep the text and formulae as concise as possible many abbreviations are used. A full list of these is given at the end of this Chapter. Care must be taken when using these formulae to ensure the correct units and that relevant constants are used. Three suffixes are used throughout for the various conditions considered. These are :

0	ISA SL (Sea Level)
S	ISA Conditions (any altitude up to 11000m)
A	Off-Standard Conditions

Standard Atmosphere

The temperatures used in the following formulae are in °K (Kelvin scale) where the ice point (0°C) is 273.15°K. To convert from °C to °K simply add 273.15.

Atmospheric properties are defined by temperature- height profiles with the general formula;

$$T = T_n + A_n\left(H - H_n\right) \tag{8.24}$$

where:

T_n is temperature at height H_n at the base of layer n
A_n is temperature gradient in that layer

In this case, with layer 0 (0-11,000m), the formula becomes:

$$T_s = T_0 + A_n.H \tag{8.25}$$

Therefore, if T_0 = 288.15°K (15°C), An = -0.0065°K/m, and H_n = 0 meters, T_s becomes:

$$Ts = 288.15 - 0.0065H \tag{8.26}$$

The pressure p_S at a pressure height H_p is given by :

$$p_S = p_0\left(\frac{T_S}{T_0}\right)^{\frac{-g_0}{A.R_A}} \tag{8.27}$$

where:

p_0	=	Air pressure at Standard sea level = 101325 N/mm^2
g_0	=	Standard sea level value for gravity = 9.80665 m/s^2
A	=	Temperature gradient = -0/0065°K/m
R_a	=	Gas constant for air = 287.05287 N.m/kg.K

the foregoing formula is derived in ESDU 68046. Combining Equations 8.24 and 8.27 we obtain:

$$p_S = 101325\left(\frac{288.15-0.0065H_p}{273.15}\right)^{5\,2558797} \tag{8.28}$$

In the Standard atmosphere the density ρ_S at pressure height H_p is given by :

$$\rho_S = \rho_0\left(\frac{T_S}{T_0}\right)^{\left(-1+\frac{-g_0}{A.R_A}\right)} \tag{8.29}$$

where:

ρ0	=	air density at Standard sea level = 1,225 kg/m3
g_0	=	Standard sea level value for gravity = 9.80665 m/s^2
A	=	Temperature gradient = -0/0065°K/m
R_a	=	Gas constant for air = 287.05287 N.m/kg.K

the foregoing formula is derived in ESDU 68046. Therefore

$$\rho_S = 1.225\ \frac{288.15 - 0.0065H_p}{288.15}^{4.2558797} \tag{8.30}$$

Off-Standard Atmosphere

In an Off-Standard atmosphere the temperature profile is defined by adding a constant increment to the ISA temperature at each pressure height. Thus;

$$T = T_n + \Delta T + A_n\left(H - H_n\right) \tag{8.31}$$

where ΔT is the increment from ISA. Therefore, in this case with layer 0 (0-11,000m), the formula becomes:

$$Ts = T_0 + \Delta T + A_n.H \tag{8.32}$$

where T^0 = 288.15°K (15°C), A^n = -0.0065°K/m, and H^n = 0 m. Therefore:

$$T_S = 288.15 + \Delta T - 0.0065H \tag{8.33}$$

The pressure in the Off-Standard atmosphere is, by definition the same as in the ISA. Therefore:

$$p_A = p_S \tag{8.34}$$

From the Gas Laws:

$$\frac{p_1}{\rho_1 . T_1} = \frac{p_2}{\rho_2 . T_2} \quad \text{or} \quad \rho_2 = \rho_1 \frac{p_2}{p_1} . \frac{T_1}{T_2} \tag{8.35}$$

and as $p_1 = p_2$ we obtain:

$$\rho_A = \rho_S \frac{T_S}{T_S + \Delta T} \tag{8.36}$$

Relative Density

The relative density is the ratio of the density of the atmosphere at any Standard or Off-Standard condition to the density at ISA sea level, i.e:

$\sigma = \dfrac{\rho_S}{\rho_0}$ for standard conditions and

$\sigma = \dfrac{\rho_A}{\rho_0}$ for off standard conditions (8.37)

Contained Gas Conditions

The contained, or lifting gas, will obviously be lighter than air. The most common gas practically used at present is helium. It is, however, unlikely to be 100% pure and will contain some impurities in the form of air. The purity of the gas is usually given as a percentage. For example 98% pure helium will be 98% by volume of helium and 2% by volume of air. The density of the gas at ISA SL is therefore:

$$\rho_{total} = k . \rho_{gas} + (1 - k)\rho_{air} \tag{8.38}$$

where k is the purity in percentage expressed as decimal (e.g. for 98% pure, $k = 0.98$). For example, if the contained gas is 98% pure helium the density is given as $\rho = 0.98 \times 0.169 + (1 - 0.98) \times 1.225 = 0.19012$ kg/m^3, where ρ_{air} is the density of air at ISA SL $= 1.225$ kg/m^3 and the density of 100% pure helium is 0.169 kg/m^3.

The density of the gas at the required Standard or Off-Standard condition is simply obtained by multiplying the ISA SL density by the previously obtained relative density.

The pressure of the contained pressure is taken as the sum of the atmospheric pressure plus the pressure differential between the inside and outside of the envelope, the pressure that gives the envelope its strength.

$$p_{gas} = p_A + \Delta p \tag{8.39}$$

$$\frac{p_1}{\rho_1.T_1} = \frac{p_2}{\rho_2.T_2} \quad \text{so} \quad \rho_2 = \rho_1.\frac{p_2}{p_1} = \rho_1.\frac{p_1 + \Delta p}{p_1} \qquad (T_2 = T_1) \tag{8.40}$$

Δp should always have a positive value (otherwise the envelope would attempt to collapse). Therefore, the effect of this pressure differential is to increase the density of the contained gas. As the mass of the gas does not change the volume it occupies 'Vn' will decrease, which will result in a reduction of both gross and net lift. The amount is small. As an example, for a pressure differential of 2in WG (498 N/m^2), the effect on gas density is to increase it by less than half a percent. This would, however, approximately equate to a reduction in lift of 50kg on a 10000m^3 airship. As this pressure differential is more or less constant throughout normal operations it does not really need to be considered - the variation in pressure differential will have an effect in the order of 0.1% and can generally be ignored. Physical determination of the airship's lifting capacity, through measurement, weigh-off or other means will include the effect of pressure differential.

The temperature difference between that of the contained gas and that of the atmosphere (superheat) can have a greater effect. It must be considered as it will be variable not only from operation to operation but could have a significant effect during a single flight. Again from the gas law:

$$\frac{p_1}{\rho_1.T_1} = \frac{p_2}{\rho_2.T_2} \quad \text{so} \quad \rho_2 = \rho_1.\frac{T_1}{T_2} = \rho_1.\frac{T_1}{T_1 + T_{SH}} \qquad (p_2 = p_1) \tag{8.41}$$

The effect is in reverse to the pressure differential, i.e. if the temperature differential is positive (unlike pressure it can be both positive and negative) the density decreases. As already mentioned, this temperature differential (the superheat) can be either positive or negative. Positive superheat (i.e. internal temperature higher than external) may arise from the aircraft being on ground in bright sunlight. The envelope will act as a greenhouse and the internal temperature rises. Similarly, if the airship has been in a hangar overnight and is then brought into the sunlight prior to flight, the internal temperature could remain below that of the atmosphere (i.e. negative superheat) for some time. As the airship flies, any temperature differential reduces and stabilises. If, however, the operation of the airship takes it from hot to cooler conditions and from sunny to dull conditions or vice versa, then it should appear obvious that the superheat can change several times. It is therefore necessary to be aware of the superheat and its effects at all important stages of the flight (take off, landing, hover, etc.).

An airship will start flying with some sort of superheat and this will usually disappear or reduce in the early stages of flight.

If an airship has positive superheat at take off the effect is to decrease the density of the gas. This increases the net volume and as

$$Lg = Vn.\rho a \qquad \text{and} \qquad Ln = Vn.\rho a - M \tag{8.42}$$

this has the effect of increasing lift. During flight, however, the superheat will reduce thus having the opposite effect (i.e. of reducing lift and increasing heaviness). If this superheat is not accounted for initially, then the airship's maximum heaviness limits may be exceeded at landing. Therefore, at take off, the amount of lift due to superheat needs to be determined.

Conversely, if the airship has negative superheat initially, then the opposite happens. As the superheat wears off the airship gains lift or becomes lighter. The superheat should be considered at take off, landing and *en-route* to ensure the airship is within its design or operational limits at all time. The effect of the superheat is significant and it is, therefore, important that it be determined as accurately as possible.

TERMS AND ABBREVIATIONS USED

The following are the terms and abbreviations used throughout this Chapter. Units and values are given primarily in the S.I. system with British/American equivalents provided in parenthesis,

A	Temperature Gradient [-0.0065°K/m (-0.0019812°K/ft)]
g_o	Standard sea level value of acceleration due to gravity [9.80665 m/sec^2 (32.1740 ft/sec^2)]
H_p	Pressure Height (m (ft))
H_z	Geopotential Height [m (ft)]
k	Helium Purity [%]
pa	Atmospheric pressure [N/m^2 (lb/ft^2)]
pa_0	Atmospheric pressure at ISA Sea Level [101325 N/m^2 (2116.22 lb/ft^2)]
pa_S	Atmospheric pressure in Standard atmosphere [N/m^2 (lb/ft^2)]
pa_A	Atmospheric pressure in Off-Standard atmosphere [N/m^2 (lb/ft^2)]
pg	Pressure of contained gas [N/m^2 (lb/ft^2)]
pg_0	Gas pressure at ISA Sea Level [N/m^2 (lb/ft^2)]
pg_S	Gas pressure in Standard atmosphere [N/m^2 (lb/ft^2)]
pg_A	Gas pressure in Off-Standard atmosphere [N/m^2 (lb/ft^2)]
Δp	Pressure differential between atmosphere & contained gas [N/m^2 (lb/ft^2)]
R_A	Gas constant for air [287.05287Nm/kg.K (3089.8114 lb.ft/slug.K)]
R_G	Gas constant for helium mix [Nm/kg.K (lb.ft/slug.K)]
T_0	Temperature at ISA sea level [288.15 K]
T_S	Temperature in Standard atmosphere at pressure height [K]
T_A	Temperature at pressure height in Off-Standard atmosphere [K]

T_g	Temperature of contained gas [K]
T_{SH}	Temperature difference (superheat) between inside [K] and outside of envelope in steady flight conditions
ΔT	Temperature difference of Off-Standard [K] atmosphere from Standard
ρa	Density of air [kg/m^3 (slug/ft^3)]
ρa_0	Standard sea level density of air [1.225 kg/m^3 (0.002376892 slug/ft^3)]
ρa_S	Density of air at pressure height in Standard atmosphere [kg/m^3 (slug/ft^3)]
ρa_A	Density of air at pressure height in Off-Standard atmosphere [kg/m^3 (slug/ft^3)]
ρg	Density of contained gases [kg/m^3 (slug/ft^3)]
ρg_0	Standard sea level density of contained gas [kg/m^3 (slug/ft^3)]
ρg_S	Density of gas at pressure height in Standard atmosphere [kg/m^3 (slug/ft^3)]
ρg_A	Density of gas at pressure height in Off-Standard atmosphere [kg/m^3 (slug/ft^3)]

9

Weight Estimates and Control

J. Craig

AIRSHIP MASS PROPERTIES

Introduction

This chapter aims to address most of the weights and other aspects of mass properties of airship design and operation, of which there are many.

The chapter will not, however, address preliminary sizing of airships, i.e. using formulae and graphs to derive a 'first stab' airship weight. As explained later, the author has concerns over the validity, efficacy and accuracy of such methods.

The importance of good weight estimation and control during all phases of the design of an airship, especially in the early stages, cannot be over-emphasised. Many people within the aircraft industry (and even within the LTA area) tend to accept the weight of an airship, sometimes simply due to its definition as a lighter than air vehicle, as of secondary concern. Yet the weight or amount by which the airship is overweight has a more direct effect on the performance than it would on a conventional fixed or rotary winged vehicle. Every additional kilogram of weight is one kilogram lost in available payload. Also, because an airship is very fuel efficient, any lost fuel capacity through this increased weight has an effect on endurance, which can be several orders of magnitude greater than for a heavier-than-air aircraft. Because endurance is one of the primary benefits of an airship - and in many cases its sole *raison d'être* - accurate preliminary weight estimation, and strict weight control, are vital.

Weight Definitions

There has been some confusion over the definitions of the various weight configurations of an airship. These should be related to the terms used for heavier-than-air aircraft, wherever possible, despite some inconsistency. The following is a list of suggested terminology for airship weights.

Bare Weight

The ‘bare weight’ of an airship is the weight of structure, powerplant, systems and furnishings that are common to all configurations of a particular airship type. There would be no difference between an airship of a particular type destined for military use or for civil use.

Bare Suspended Weight

The ‘bare suspended weight’ of an airship is the suspended weight of structure, powerplant, systems and furnishings that are common to all configurations of a particular airship type.

It should be noted that the suspended weight is a critical design criterion for airships. For this reason, a ‘suspended’ equivalent is included for most of the definitions above. Where ‘suspended weight’ is mentioned in the definitions it refers to the weight of all relevant items acting through the suspension system.

Manufacturer's Empty Weight

The ‘manufacturer’s empty weight’ (MEW) is the Weight of structure, powerplant, systems, furnishings and other items of equipment that are an integral part of a particular airship configuration. Only fluids contained in closed systems are included as well.

Manufacturers Suspended Empty Weight

The ‘manufacturer’s suspended empty weight’ (MSEW) is the suspended weight of structure, powerplant, systems, furnishings and other items of equipment that are an integral part of a particular airship configuration. Only fluids contained in closed systems are included as well.

Basic Empty Weight

The ‘basic empty weight’ (BEW) is the manufacturer's empty weight plus weight of standard items.

Basic Suspended Empty Weight

The ‘basic suspended empty weight’ (BSEW) is the manufacturer's suspended empty weight plus the weight of suspended standard items.

Standard Items

The 'standard items' are equipment and fluids which are not an integral part of a particular airship configuration and not a variation for the same configuration. These items include:

- Unusable fuel and other unusable fluids.
- Engine oil.
- Fixed ballast.
- Toilet fluid and chemicals.
- Airship emergency equipment.
- Galley structure, etc.
- Supplementary electronic and avionics equipment (for a particular configuration).
- Fixed mission equipment and armament not included in MEW.

Operational Empty Weight

The 'operational empty weight' (OEW) is the basic empty weight plus operational items.

Operational Suspended Empty Weight (OSEW)

The 'operational suspended empty weight' (OSEW) is the basic suspended empty weight plus suspended operational items.

Operational Items

The 'operational items' are Personnel, equipment and supplies necessary for a particular operation but not included in the basic empty weight. These operational items may include:

- Disposable ballast.
- Crew and baggage.
- Manuals and navigation equipment.
- Removable service equipment for cabin, galley and bar.
- Food and beverages.
- Usable fluids other than those in basic empty weight.
- Personal emergency equipment.

- Special mission equipment, weapon racks, etc. not included in basic empty weight.

Operational Take-off Weight

The 'operational take-off weight' (OTW) is the operational empty weight plus disposable load at take-off.

Disposable Load

The 'disposable load' is variable for a particular operation. This will include passengers, luggage and cargo, whether revenue or non-revenue, additional (non-essential) crew and additional carry-on mission equipment.

Maximum Operational Take-off Weight

The 'maximum operational take-off weight' (MOTW) is the maximum authorised weight for take-off. It is subject to airport, operational and related restrictions.

Maximum Operational Landing Weight

The 'maximum operational landing weight' (MOLW) is the maximum authorised weight for landing. It is subject to airport, operational and related restrictions.

Maximum Design Suspended Weight

The 'maximum design suspended weight' is the maximum weight that can be suspended or supported by the suspension system.

Maximum Design Operational Weight

The 'maximum design operational weight' (MDOW) is the maximum weight of the airship regardless of any operational or related restrictions. It shall not be less than the MOTW.

Gross Weight

The 'Gross weight' of an airship is the total weight of the aircraft including enclosed gases (lifting gas and ballonet gas). It is equivalent to the gross buoyancy plus static heaviness (or less static lightness).

DESIGN CONSIDERATIONS FOR WEIGHT

Introduction

It is not unusual, though unreasonable, to have to derive an airship weight estimate before any schemes have even been started - possibly from just a single vague paragraph. In this situation, apart from attaching as many disclaimers as possible to the weight estimate, it is advisable to be aware of the factors that will affect the weight and produce a set of assumptions that are going to be used.

Pre-design Considerations

As in all vehicular projects, feasibility studies need to be carried out. For airships, widely different roles are always being proposed, many of them ambitious in nature. For all these studies, however, it is important that they are approached in the right manner. The first step is to determine the feasibility of the proposal. If the proposal is completely impractical, then it is not worth taking it any further. Many proposals, however, initially seem impractical but with some clarification can become workable. The first step must be to discuss with the client the requirements of the airship or proposed mission and agree these in writing. Only when these requirements are as clear as possible, can the criteria be derived which will allow the weight to be estimated.

Design Criteria

Before any design or estimation work is carried out, it is vital that the design criteria are clearly established or derived. These criteria can be divided into those that should be considered mandatory and those that are preferred though not mandatory. The consideration of these basic design criteria should include:

- Payload (explicit and implied).
- Endurance.
- Performance.
- Operational environment (altitude and temperature ranges).
- Maximum weights.

It is well worth the effort to ensure that these criteria are well defined and understood, as they can save a great deal of frustration at later stages of the design. Some of the above criteria are dealt with in detail elsewhere in this book but a weights overview is given below.

Payload

The payload comprises all the equipment (fixed or removable) that is required for the proposed mission plus all ancillary systems and support structure (which may be needed for the mission to be completed, even though they will not be part of the bare airship structure). The payload could be civil or military. It is just as important to account for the implied payload which is not explicitly stated but would be required to ensure successful operations. The following lists should be considered as guidelines.

Civil Items

- Seating - number and type, e.g. high capacity or luxury.
- Interior trim level.
- Toilet facilities.
- Additional cabin crew.
- Galley facilities.
- Refreshments.
- Safety equipment - life jackets, rafts, etc.
- Supplementary advertising - banners, night signs.
- Additional avionics - because an item is not explicitly stated does not mean that it will not be required, e.g. night time operations on an airship only certified for VFR will require certification with additional avionics (and lighting).

Military/Paramilitary Items

- Supplementary electronics/mission equipment:
- communications, navigation, etc.
- Electronic power requirements: the need for additional electrical generation capacity, and type of supplies required (inverters, phase sequence units, etc.).
- Cooling requirements, both for cabin and electronics which have an effect on power requirements).
- Additional crew.
- Safety equipment: life jackets, rafts, etc.
- Crew accommodation and facilities: seating, toilets, galleys, bunks, etc.
- Underway replenishment (Unrep) requirements: dependent on endurance and operational requirements.

- Auxiliary fuel capacity - again dependent on operational requirements - may need several design iterations to determine the optimum.
- Protection: both passive (stealth technology, armour, etc.) and active (missiles, etc.).
- In service/flight maintenance requirements.

An incomplete, or inaccurate, assessment of the payload or mission requirements could result in the weight being underestimated, which could jeopardise the feasibility of a programme. The importance of this aspect cannot be emphasised enough.

Endurance

The required endurance will not only drive the fuel requirements but also payload considerations such as crew numbers. For example, will the required mission period require double crew, and facilities for crew and passengers? Or, should bunks and hot food be provided? It is important to be aware of what the operational conditions are for the endurance requirements. For example, is the endurance required for the total or the on-station requirement? If on-station, what are the transit requirements? What wind conditions are to be used? The required endurance, along with performance, will be a major deciding factor in the choice of engine configuration and type.

Performance

Performance, endurance and mission payload requirements can be combined to produce a mission profile. This mission profile could dictate payload and, therefore, approximate maximum lifting capability, pressure height, time on station, speed or time to station, etc. A first estimate could then be made of envelope and ballonet volumes, gondola size, and engine specifications (numbers, power and configuration). This should be one of the first steps in deriving a new design - though it must be admitted the process is not usually this pure, and the final design includes many compromises. For a more detailed discussion please refer to Chapter 13 which is devoted to Performance.

Operation Environment (Altitude and Temperature Ranges)

Careful consideration must be given to the expected range of pressure heights and temperatures including diurnal temperature ranges. This is to ensure that there is enough lift available and that the ballonet capacity is adequate to handle the required ranges.

Maximum Weights

The maximum weights should be decided early on. These should include both the maximum design operational weight and the maximum design suspended weight. Both are likely to be used early in the design phases, and it makes sense to avoid altering them at later stages.

The maximum operational weight should be at least equivalent to the maximum available lift under the required operational environment. As a guide, between 0.9 and 1.0 kg/m^3 of envelope volume should cover most realistic cases.

The maximum design suspended weight will, amongst other things, size the suspension system. Again, it is important to fix this item so as to avoid changes later - which could involve a substantial amount of design and production modification - whilst avoiding steps that might produce 'over the top' suspension systems.

WEIGHT ESTIMATION

Introduction

It is not the intention of this chapter to provide readers with formulae, graphs and charts enabling them to derive, without much consideration, preliminary weight estimates for the component parts of a modern airship. The main reason for this, as already mentioned, is validity and accuracy. It is important, far more so for an airship than a heavier-than-air aircraft, that the vehicle is not overweight. One of the primary tools in controlling the weight is an accurate and realistic preliminary estimate. Unrealistic estimates will cause trouble throughout the remainder of the design process.

There are several reasons why this type of preliminary weight estimation can be problematic. Firstly, there is a lack of recent historical data for airship weights covering non-rigid, semi-rigid and rigid airships making the derivations of parametric links complex and sometimes tenuous. Tied into this are the technological advances and increasingly complex demands being made in and on airships. Unfortunately these requirements, whilst reducing workload and improving performance, reliability, safety and manoeuvrability, both in the air and on the ground, have produced an upward trend in the weight of modern airships. This would, when using parametric data based on previous airships, produce a light estimate. Additionally airship design is more flexible throughout the design period with a greater number of possible configurations being considered than might be the case with a conventional fixed wing aircraft. And finally, comparisons cannot reasonably be made with other types of fixed or rotary wing vehicles.

Having stated what this section will *not* be doing, it is only fair that the reader now be told what *can* be expected from it. The aim has been to guide the engineer or designer in deriving a weight estimate for an airship based on its role. Where the author has considered that sufficient data are available to enable reasonable estimates to be made, then these are given. In general, however, information is provided on how to derive the weight estimate, what considerations and assumptions are fair and what pitfalls to avoid.

Hull Group Weight Estimation

Owing to lack of available data on modern rigid and semi-rigid hull designs this section is primarily concerned with the weight estimation of non-rigid hulls. It is hoped that this section will not only allow initial weight estimates to be derived but give the reader some guidance on the factors affecting the hull group weight.

A note on scaling: for envelopes of the same profile, linear dimensions can be scaled using:

$L2 = L1\ (V2/V1)^{1/3}$ and areas by $A2 = A1\ (V2/V1)^{2/3}$.

Envelope Design Criteria

Like all aspects of the airship design it is important that, in order to derive a realistic weight estimate, the criteria which are going to apply to the design of the envelope are defined. The following information should be known, or at least well documented assumptions used in its place.

- ***Envelope volume.*** For the purpose of estimating the weight of the envelope components, it would be reasonable to add 6% on to the top envelope volume. This equates approximately to just 2% on linear dimensions. This assumption should only be used for the derivation of weights and not, for example, when calculating lift.

- ***Ballonet volume***. This would be dependent on the range of operational conditions, primarily pressure height. Again it is recommended that a tolerance of +6% be used.

- ***Ballonet configuration***, e.g. fore, aft and/or pannier ballonets and their relative capacities.

- ***Suspension system details***. Primary maximum suspended weight (gondola). Primary suspension configuration (internal or external, adjustable, etc.). Secondary suspension/attachment requirements - will there be requirements to suspend equipment within or from the envelope or attach equipment, e.g. nightsign, to it?

- ***Access and maintenance requirements***. For example, if it is intended that large items are to be carried within the envelope, then possibly a large access panel would be required in the envelope fabric. Similarly, if there is a requirement for in-flight maintenance, then this implies access into and possibly onto the top of the envelope.

Non-Rigid Envelope Weights

Table 9.1 gives a tabular weight breakdown of hull assemblies for airships with approximate volumes of 350,000 ft^3 (10,000 m^3) and 2,500,000 ft^3 (70.800 m^3). These data are based upon well defined designs with, in the case of the smaller airship, some actual weights. The data will be used and expanded on in the following paragraphs. Table 9.2 contains basically the same data, but shows each major sub-assembly as a percentage of the total.

Table 9.1. *Hull Assembly Weight Breakdown*

	Component Weight (kg)	
Airship Volume ⇒	**10,000m^3**	**70,800m^3**
Hull Assembly ⇓		
Fabric Structure	1,497	7,024
Suspension System	110	927
Nose Reinforcing Group	209	1,244
Gaiters	8	160
Access/Maintenance	12	280
Conduits	30	96
Miscellaneous	32	95
Sub-Total	1,898	9,826
Air/Helium Valves & Clamp Rings	90	460
Total	1,988	10,286

Table 9.2. *Percentage Analysis of Major Sub-Assemblies*

	Component Weight (%)	
Airship Volume ⇒	**10,000m^3**	**70,800m^3**
Sub-Assembly ⇓		
Fabric Structure	75.3	72.5
Envelope		49.0
Ballonet - 24%		
Ballonet - 36%		13.7
Load Curtain		7.4
Reinforcing Patches, Etc.		2.4
Suspension System	5.5	8.8
Nose Reinforcement	10.5	11.8
Access/Maintenance/ Gaiters	1.0	2.4
Conduits	1.5	0.4
Clamp Rings	4.5	3.0
Miscellaneous	1.6	1.0

Fabric Structure

The fabric structure is the largest component of the hull and consists of:

- Envelope fabric.
- Ballonet fabric.
- Airlines.
- Catenary curtains.
- Patches and reinforcements, etc.

It is almost impossible to calculate a detailed weight for the 'final' structure until it has been fully detailed (by which time it has probably been manufactured and weighed). It is hoped that the following few paragraphs will give enough information to allow a relatively accurate weight estimate in the early stages, requiring a few modifications as the information becomes more detailed.

Envelope Fabric

This comprises the gores making up the envelope profile, the seams, patches and reinforcements. The envelope fabric weight is simply the surface area of the envelope multiplied by the net density of the fabric.

Because of its large effect on weight, it is important that the **surface area** of the profile be determined as accurately as possible. If the formulae defining the profile are known, then the surface area can be obtained by integration using numerical methods such as Simpson's Rule. Great care, however, must be taken to ensure the elemental length ds and *not* dx is used. To use dx (which the author has seen done many times by experienced and knowledgeable engineers) would result in a significant underestimate of the surface area and, therefore, the weight.

If the envelope profile has not been defined then an approximation for the surface area can be obtained from:

$$\text{Area} = 9.719\, p\, (V/10.917)^{2/3} \tag{9.1}$$

where: V = Gross Envelope Volume

The net area **density** of the fabric, including allowances for seams, patches, etc. should be in the range 0.35 kg/m^2 to 0.52 kg/m^2; the greater the volume the higher the density. It is recommended that rather than use a straight line graph of density against volume that the figures in Table 9.3 be used.

Table 9.3. *Area density of envelope fabric versus volume*

Volume (m^2)	Area Density (kg/m^2)
up to 16,000	0.35
16,000 - 30,000	0.40
30,000 - 60,000	0.46
60,000 - 85,000	0.52

Ballonet Fabric

The weight for ballonet fabric is more complicated to estimate accurately without details due to their relatively complex shape. Additionally there are many different possible ballonet configurations. The data provided here is based on 'conventional' forward and aft and pannier ballonets. Like the envelope fabric the ballonet fabric weight can be obtained by multiplying the surface area by a net density.

The **surface area** for ballonets has to be considered carefully. A ballonet of a certain volume will have differing surface areas if in envelopes of different volumes (due to change in envelope profile). The formula provided here should give a pessimistic surface area. For forward and aft ballonets an approximate surface area can be obtained from:

$$\text{Area} = 1.07pV^{2/3}$$

and for pannier ballonets from:

$$\text{Area} = 3.75\,p\,(3V/5p)^{2/3}$$

The net area **density** of the ballonet fabric (including seams) is between 0.275 kg/m^2 and 0.305 kg/m^2 the larger the ballonet the lighter the net fabric density.

Airlines

These are the fabric tunnels which take the air into the ballonets. They represent only a small fraction of the envelope fabric weight (2%-3%).

Catenary

This is the fabric structure from which the suspension cables are hung. The weight depends on the complexity and would vary between 9% and 14% of the envelope fabric weight, the larger the airship the higher the percentage.

Patches, Reinforcement, Etc.

This will depend on the complexity of the envelope but an allowance of between 2% and 5% of the envelope fabric weight should be made. Again the larger the airship the higher the percentage.

Suspension System

This covers all the items allowing the suspension of the gondola from the envelope, though excluding the catenary itself. But again, there are a variety of possible configurations for the suspension system and for the manner in which it is attached and adjusted. Ideally, an estimate, no matter how preliminary, should be made against some sort of scheme - as with most aspects of the preliminary weight estimating discussed in this chapter - to do so without a preliminary estimate will almost certainly lead to difficulties. For those, however, who insist on diving into the quagmire it is suggested that a figure between 10kg and 13kg for each 1,000m^3 of envelope volume be allowed for a suspension system, the higher figure for larger and/or more complex suspension systems. These figures are based on a conventional gondola being suspended beneath the envelope and carrying all or most of the payload (making the suspended weight approximately directly proportional to the lift and, therefore, envelope volume).

Nose Reinforcement Group

This is considered to consist of a nose cone and mooring probe and a structure consisting of battens or the like. There is no allowance in the figures that follow for structure, etc. for any additional systems that may be mounted on the nose. Again, basing the weight on the envelope volume, an allowance of between 17kg and 21kg per 1,000m^3 of envelope volume; the higher figure should be used on smaller airships (approx. 6,000m^3) whilst the lower figure should be used on larger airships (70,000m^3) using a linear extrapolation for other volumes.

Access/Maintenance

This will depend not only on the size of the airship but also on its intended use. For example, a small civil airship will require minimal access for ground inspection and maintenance with possibly no more than some sort of viewing aperture. A large military airship, with long endurance capabilities, would almost certainly require access not only into the envelope, but also on to the top with associated facilities allowing limited maintenance and repair. Care must, therefore, be taken when estimating the weight for this aspect of the hull. The weight allowance for the aforementioned small airship might only be 10-15kg, less than 1% of the total hull weight; whilst that for the larger airship could easily be around 300 kg, almost 3% of the total hull weight.

Others

Allowance must be made for all sorts of other items fitted to the envelope, irrespective of size and complexity. Examples of such extras include fill valves, rip systems, through fabric gaiters and cable conduits. It is recommended that an allowance of 5% of the weight of the hull group obtained so far be made, and that another 3%-5% for contingency be added (inconspicuously).

Paint

Painting the envelope is to be avoided. The weight effect of paint is often substantially underestimated; there can be large variations in the weight of the same area painted using the same paints on different airships. Painting cannot always be avoided, however, because of the requirement for environmental protection of the envelope fabric. Paint can weigh between 0.08kg/m^2 and 0.12 kg/m^2 when on an envelope. As it will not be possible to weigh the airship after the envelope is painted, care must be taken to attempt to monitor the weight during the painting by taking samples, etc. and conducting a comparative weigh-off.

Where it is intended to paint the envelope for 'decorative' purposes, the use of decals should be investigated. Although there may be no initial weight benefit decals can be removed when the decor changes. Paint, however, will generally be painted over, thus increasing the empty weights of the ship every time the decor is altered.

Tail Group

Great care has to be taken when estimating the weight of the tail group. Owing to its large moment arm, any inaccuracy in the tail weight not only affects the weight of the airship but also has a substantial effect on the balance. If this happens, the alternatives are either to reposition the tail or the gondola so as to offset the imbalance (extremely unlikely), or to accept reduced control and performance (if imbalance is small) or add ballast. If the ballast can be mounted in the nose then the required amount of ballast will be around 80% - 100% of the tail weight error. This effectively doubles the amount by which the tail is overweight, hence the importance of **realistic** weight estimates (a light tail could be ballasted up to its correct weight but again this is a waste of weight that could otherwise be made available for payload).

Tail Structure

The typical tail structure comprises a structural framework covered by some sort of fabric to keep the aerodynamic properties. A survey of fins over a period of two decades indicates a structural weight density in the range 4.9 - 5.4 kg/m^2 (this is for the fin structure complete, i.e. including control surface). Some more recent designs, however, have a structural area weight density between 5.6 and 6.6 kg/m^2. This higher weight can be put down to higher loads in the fins owing to increased performance and manoeuvrability. For a modern airship design, the weight of the fin structure (no fittings, etc. and assuming a frame and skin structure type construction) should be estimated using 4.9 kg/m^2 for small 'low' performance airships, 5.9 kg/m^2 for smaller higher performance airships (5,000m^3 - 20,000m^3) and 5.6 kg/m^2 for large airships. Although these differences may appear small their effect can be considerable. For example, an increase of 0.5 kg/m^2 on a 10,000m^3 airship could result in an increase in the total tail structure of over 70kg and moment about the CB of 1,700 kg.m. Allowing for ballast to counter the resultant imbalance, the total weight increase would be about 125 kg (between 1 and 2 persons or enough fuel for several hours cruising).

An alternative design being promoted is the pressure contoured fin developed by an American company, ARDCO. These promise a fin structure weight up to 20% less than the figures quoted above. Additionally, if these pressurised fins are filled with helium, there could be an added advantage of an extra $100m^3$ of lift volume on a $10,000m^3$ envelope (though loss of helium from the fins would result in an imbalancing moment and must be considered carefully). Caution should be exercised in assuming this type of design and associated weights until it has been proven in a production environment.

Whichever type of design is being proposed the following components must also be considered with the fin group:

- ***Control Surfaces.*** Will the control surfaces be one piece or split? If split, the structure weight will be up slightly; also there will be additional control surface actuation requirements.

- ***Control Surface Actuation***. The actuators or actuation method is discussed later in this chapter. There must be allowances for mounting the actuators in the tail and possible lightning strike protection, especially if fins are mainly composite.

- ***Strobe and Navigation Lights***. Allowances must be made for strobe and navigation lighting, even though it is a small amount.

- ***Tail Rigging***. Approximately 4 - 5.5% of the total fin and control surface structure weight should be allowed for tailfin rigging. This does not include reinforcement patches on the envelope fabric.

Gondola and Associated Structure Group

Owing to the great flexibility available from airships, the gondola, or equivalent payload carrying module, can come in a wide variety of configurations. It is not in the scope of this chapter to enter into any detailed investigation of the weight implications of the various configurations. What follows is a discussion of the factors that may affect the design, and therefore the weight, of the gondola structure. There is also additional information relating to 'conventional' suspended type gondolas.

Factors to be Considered

It is important to consider carefully what is expected from the structure and how this will affect the weight. The following is a list, which should be used as a guide only and should not necessarily be considered comprehensive. Many proposed applications will drive the design towards a very specialised solution.

- ***Configuration and Location of Gondola***. As already mentioned, there are many possibilities though not explained here in detail. It is important,, however, that the static trim of the airship *(when typically loaded)* is considered and the location of the gondola positioned accordingly.

- ***Suspension/Attachment to Envelope.*** How is the gondola to be suspended? If from suspension cables, will the cable locations and angles dictate a minimum structure length and width?

- ***Purpose of Airship***. Is the airship intended to carry passengers and mission crew, which will dictate a protected environment, or is it intended to carry particular equipment, which could be handled by some form of skeletal structure? If an enclosed structure, then what is a realistic volume for the 'cabin' and will it require to be pressurised?

- ***Location of pilots.***

- ***Propulsion System.*** Will the propulsion system be located, all or partly, in the gondola, and if so would this result in requirements for outriggers?

- ***Fuel Tankage***. What volume would be required for fuel within or, in the case of external or auxiliary fuel tanks, attached to the gondola?

- ***Ballast***. Will space and associated structure be required for ballast, especially water?

- ***Landing Gear***. What is the proposed configuration of the landing gear?

- ***Other Systems***. What systems will be located within the gondola structure?

- ***External mountings.*** Is the proposed mission(s) likely to require external mounting of such items as radar and other sensors, auxiliary fuel tanks, etc.?

Structural Weight Approximation

Obviously, the weight for a gondola structure cannot be accurately estimated from a set of formulae without the inclusion of many variables. It is much more sensible to consider carefully the points raised in the preceding paragraph and sketch a scheme for the gondola that meets the derived requirements. A fair weight estimate should be obtained from this scheme and from assuming conventional aircraft structural design and technology. If advanced composite materials are proposed then the scheme should be considered more carefully and a sensible contingency be allowed.

Cabin Weights

The cabin is taken as the part of the structure, which will contain the payload whether it is passengers and cargo or the mission equipment. When considering cabin structure, it is worth remembering that the larger the airship and cabin the more complex the structure is likely to become. Great care must, therefore, be taken if scaling up. Weights for a wide variety of gondola sizes, from cabin volumes of less than $30m^3$ to greater than $350m^3$ have been investigated expecting some sort of square relationship between cabin cross sectional area and weight. In fact, owing to this increase in structural complexity, the figures for all the cabin design studies had very similar weights per square metre of CSA. Allowing for flight deck structure, this came out at about 10.5 kg/m^3 to 11 kg/m^3.

When considering the weight for the cabin structure, the following should be noted:

- ***Floors & Ceilings***. The weight of these panels and their support can easily be underestimated.

- ***Doors & Windows.*** The weight of these, especially doors, can be substantially greater than supposed. Account must also be taken of local reinforcing in the surrounding structure.

- ***Insulation***. Both noise and thermal insulation become more important as flights have longer endurance or achieve higher altitudes. Insulation could be accounted for either within the structure or in the furnishings and equipment group.

- ***Bulkheads***. Internal structural panels. 'Decorative' bulkheads are usually accounted for in the furnishings and equipment group.

- ***Trim Panels.*** These are internal panels on external structure.

- ***Ballast Structure***. On larger gondolas, the under-floor structure could be used for water ballast storage. If that is proposed, then allowance must be made for additional structure in this area.

- ***Equipment Mounting***. If there is going to be mission equipment mounted within the cabin, then there should be suitable allowance for reinforcement.

Fuel Tankage

For fuel tankage space, which will almost certainly require additional structure, it is not unreasonable to allow between 35% and 50% of the derived linear weight for cabin structure. This figure does not allow for any fuel bladders, plumbing, etc., which are considered part of the fuel system group rather than car structure.

Engine Bay

Engine bay structure must be considered very carefully as this can have a substantial effect on weight. These considerations must include:

- ***Engine Mounting.*** Will it be fairly straightforward or will sub-frames, etc. be required?

- ***Fire protection***. Engines mounted within the gondola will need to be contained within heavy fireproof bulkheads.

- ***Access space.*** Will additional structure be needed for cooling, maintenance, access, etc.?

- ***Pylon***. Some sort of pylon structure may be required on which to mount the propulsor. What additional equipment may be mounted on this outrigger structure, and how will it be attached to the gondola?

Other Factors

- ***Equipment Bay***. Structure required to house both ship's and mission equipment. This could involve heavy avionics racking. Why do they have to use so much steel?

- ***External mounting of heavy equipment*** such as radars, winch equipment, auxiliary fuel tanks, etc.

- ***Fitting of ships systems***, i.e. electrical equipment, pneumatics systems, ECS (environmental control system), ballast tankage and equipment.

- ***Mounting of landing gear***. Could involve substantial reinforcement.

Propulsion System

Introduction

Weight must be a serious consideration in the choice of powerplant and in the design of the propulsion system. It is important that the powerplant is considered, not only in conjunction with the other components of the propulsion system, but also with the fuel load for required missions. A lightweight engine may look initially attractive. If, however, its SFC in the required operating ranges is higher than a heavier engine, then the total combination of engine weight plus required fuel may be greater than might be obtained from a heavier, though thriftier, engine. This emphasises the point raised in the introduction to this chapter that it is vital that the required mission be well defined before the design should begin in earnest.

Like all the sections within this the weights chapter, the choice, configuration, location, etc. of the propulsion system is considered primarily from the weights viewpoint. The weights engineer should not be making the decision as to which is the best propulsion system for the airship That, strangely enough, is the job of the relevant designer/engineer. The weights engineer should be ensuring that the knock-on effects concerning weights are raised and, thereby, help making sure that the best compromise is reached in the design of the propulsion system. It is hoped that the following paragraphs will aid this aim.

Powerplant Choice Considerations

Type

Both piston (diesel and petrol) and turbine engines could be, and have been, used in airship applications. The following sections will outline points to be considered when choosing a type of engine.

Power and Speeds

The output power of the engine as such is unlikely to concern the weights engineer unless it is grossly over the required weight In the author's experience it is usually the reverse, i.e. the airship tends to be under-powered. This in itself, though, can lead to problems for the weights engineer as modifications to increase power output can have a substantial weight penalty, which could easily make the resultant installation heavier than if a more powerful engine had been chosen initially. Power requirements through all stages of a flight must be considered, e.g. if low cruise speeds or power requirements on station are required, it is more efficient to run engines at lower power or consider a third cruise engine.

Fuel Consumption (and Fuel Type)

It is obvious that the fuel consumption is of prime importance; on an airship, however, owing to the inherent fuel efficiency (very little power requirement for lift) it is even more so than is usually granted. It is, therefore, advisable when considering propulsion systems to include an investigation of the weight of the propulsion system plus the required fuel for the typical mission - it makes little sense choosing an engine that is 50 kg lighter, for example, if it requires 100 kg more fuel for the typical mission.

Another consideration is the type of fuel. Not only is it preferable to have a less volatile fuel on board but for airships, where it is often necessary to be able to dump ballast to equalise, it makes a great deal of sense if fuel can be used as disposable ballast.

Location

Performance is obviously the prime criterion when locating the airship propulsor. The weights engineer, however, will have to think about associated effects on structure and systems when considering propulsor location.

Considering the **gondola mounted inboard** (propulsors outboard), the gondola mounted propulsion systems have many advantages:

- Minimal additional mounting/installation structure.
- Near probable fuel system supply.
- Shorter control and indication/warning system runs.
- More efficient mounting of ancillaries such as electrical, pneumatic and hydraulic generation.
- Ease of maintenance and reduction of associated structure and equipment required.

As expected it also has disadvantages:

- Fire containment and protection. Adequate bulkheads and fire containment will be heavy.
- Noise (& Vibration Isolation). With inboard engines it will be necessary to make allowances for isolation of noise whether for civil passenger or military or para-military missions.
- Transmission system. It is almost certain that at least one gearbox will be required changing direction of motion. Gearboxes can be extremely heavy (and introduce losses in engine performance).
- Cooling. Inboard engines are almost certainly going to require outboard mounted cooling (& lubrication systems).
- Rear mounted propulsors are possible, even though they are unlikely to provide any weight advantages over outrigger mounted propulsor systems.

Now we consider the **Gondola, outboard mounted;** what is meant or inferred by this is that the engine is mounted directly behind the propulsor. As the engine will be mounted in the airflow of the propeller this configuration will only be suitable for engines with a small frontal area. It has many weight advantages:

- Small (or no) transmission system being mounted directly in line with propulsor - also improves engine efficiency.
- No space is required within gondola thus reducing structural mass considerably (even when allowing for increased pylon weight).
- Improved engine cooling thereby reducing requirements for the cooling system.

- Reduced cabin noise and vibration.
- Reduced fire containment.
- Improved access for maintenance.

Again there are disadvantages:

- Additional complexities in engine driven ancillaries such as pumps, generators, etc.
- Generally longer control cable and fuel line runs.

Although, as can be seen in terms of weight, the advantages outweigh the disadvantages for engines which can be mounted in this way.

Considering the case of **envelope mounted (outriggers)**: although this configuration is more suited to rigid or semi-rigid airships, it could be employed on non-rigid airships. The main benefit of such an arrangement is improvement in propulsor efficiency, though other benefits include reducing the ground clearance required (reduction in landing gear weight) and improvements in noise and vibration isolation. Disadvantages include: mounting structure required, isolation of engine mounted ancillaries, longer fuel and control cable runs, and more difficult access.

Considering the case of **envelope mounted (rear of envelope)**; this is one of the most efficient locations for mounting a propulsor. It is also, however, one of the most awkward locations for other reasons. It is probably best suited as a location for a cruise engine.

Fluids

Fluids, oil and coolants, whether trapped or disposable, should be carefully considered, especially for more powerful engine installations and for long endurance flights. Engines with a high oil consumption could require a substantial amount of lubricant to be carried on a long endurance flight.

The above shows the many considerations that have to be kept in mind when designing a propulsion system. The effect of variation on weights can be great, and it is important that the weights engineers assess the implications as best, and with as much detail, as possible.

Bare engine weights can easily be obtained from trade sources or reference books. Bare weights are limited in use as it is the installed weight which should be used for comparison. As mentioned above the combined weight of engine installation and required mission fuel load must be considered and charts are given for this in the chapter on Performance.

Table 9.4. *Installed engine weight allowance*

	Small (kg/hp)	Large (kg/hp)
Basic Engine (Bare Engine + Mounts	0.65	0.90
Installed Engine (Basic engine + Exhaust + Cooling + Start + Lube Etc.)	0.90	1.20
The figures above exclude transmission, propulsor, etc. as these depend on the configuration. This data is for reciprocating type engines. For small turbine powerplants, the basic engine weight is at the high end of the numbers, whilst the installed weight is at the lower end or even slightly below.		

Propulsor

This is the propeller and duct (if relevant). Shrouding the propeller with a duct can improve propulsor efficiency whilst having additional benefits of improving safety, both directly (extremely good protection afforded to ground crew and passengers on ground) and through additional protection to the airship structure in case of propeller break up. and also reducing propeller noise. There is some weight penalty from having a duct, though any such penalty is likely to be offset by efficiency improvements.

Table 9.5. *Approximate weight of propeller and duct*

Propulsor Item	Weight kg/hp	Comment
Unducted Propeller	0.14 - 0.21	min. 120 hp
Ducted Propeller	0.10 - 0.15	Propeller only, min. 120 hp
Duct	0.30 - 0.45	Duct only

The larger the propeller the lower the weight, whilst the reverse is true for ducts, i.e. the larger the duct the higher the weight. It must be emphasised that these figures are approximate; calculated estimates must be made as soon as information is available.

Transmission Systems

Transmission systems can differ substantially depending on the requirements placed on them and the configuration of engine and propulsor. Where the engine is directly in line with the propeller, the gearbox, if required at all, will be a very small affair. For an inboard mounted engine and outboard propulsor, the transmission system could consist of transmission shafts, accessory drive gearbox and at least one gearbox to accommodate a change of direction.

Assuming an inboard engine/outboard propulsor configuration then for approximation purposes the following can be assumed:

- For a ***simple transmission*** system with no separate accessory gearbox, a weight of between 0.14kg/hp (for lower hp) and 0.20 kg/hp can be used.

- For a more ***complex system*** including accessory drives, a figure of 0.25kg/hp to 0.30 kg/hp may be used.

Vector Systems

Vectored thrust, where the propulsor can be swivelled, is becoming increasingly common in modern airship designs. Although it tends to be only a small part of the total propulsion system weight, between 4% and 6%, it still needs accounting for. Based on the weight of the propulsor system, the vector system weight is between 0.12 and 0.16 kg per kg of vectored mass.

Fuel System

The fuel system is considered to consist of the fuel tankage (but not the structure), pipes and fittings, refuelling and fuel jettison systems, monitoring and control. Again, as the airship size or at least the fuel quantity becomes greater, the complexity of the system increases. Whereas small airships can get by with single fuels tanks with minimum transfer pipe-work etc., large systems could have many tanks requiring complex plumbing and fuel transfer system. When estimating the tank volume, allowance must be made both for vent space and for feeder tanks, which may be required. It is also worth bearing in mind potential requirements for either auxiliary fuel tankage and refuelling during flight or making the necessary allowances for additional equipment.

Control System

The control system primarily consists of the flight control system (FCS). Other control items include envelope pressurisation, trimming and engine/power control. The control systems become more complex the larger the airship and the greater the use of advanced technology. On larger airships, where the increased complexity and much greater cost can more easily be justified, much of the work will be done by computerised systems.

Primary Flight Controls

The primary flight control systems are responsible for the control surface movement (and monitoring). Here we will consider them being moved either by cables, direct input, or by remote actuation. On smaller airships, considering the weight implications alone, a simple cable operation system has the advantage. It has, however, many more design and performance disadvantages when considering some of the more taxing operations, especially military or para-military applications. When considering the weight of a cable operation system, take into account the number of cables (redundancy in the system), pilot input (control yoke and pedal box) and emergency operation.

There are more system components and requirements to be considered with a remote actuation system, namely:

- ***Actuator Power:*** This could be either electrical or pneumatic. Currently available pneumatic actuators tend to be unsuitable for strenuous control surface applications and, therefore, an electrically powered actuator would be required. A significant weakness in having electrically powered actuators is the need for an electrical power supply. Such a supply carries a substantial weight penalty through both the power cable itself and any braiding fitted to allow for lightning strike transmittal. At least two cable runs would normally be fitted to provide the necessary level of redundancy and therefore safety in the system. A solution to this would be to provide a local (to the actuator) source of electrical power. Batteries are not only extremely heavy but are impractical owing to their limited life. A practical method would be to employ small generators, mounted in each fin, powered by pneumatics. This will obviously add the weight of these generators to the tail and a suitable pneumatic power source will be required. If these pneumatic driven generators also supplied power to the strobe and navigation lights, etc. then all the extremely heavy power cable and braiding could be replaced by extremely light plastic piping carrying the pneumatic supply. Details of possibly pneumatic power supply systems are covered in separate sections.

- ***Actuators***: Again, owing to the moment effect, the weight estimate for the actuators should be as accurate as possible. It is advisable to obtain an idea of the loads from the control surfaces to allow some sort of sizing of the actuators. It is also advisable to try and obtain some idea of any locally mounted electronics that may be required, such as drive units, filters, etc.

- ***Signal Cables***: Cabling will be required to provide control input signals to the actuators and also to return status data, such as control surface position. This can be handled by fibre optics, again relieving the need for any electrical contact between the gondola and the fins. Employing fibre optics will, however, require the use of some sort of computer system to translate the signals.

- ***Computer system:*** Some sort of computer control system will be required for an actuation system as described above.

Envelope Pressurisation

The main components of the control of the envelope pressurisation are: (a) the control of the air and helium valves, (b) control of the ballonet air distribution (i.e. directing air forward or aft, etc.) and (c) scoop operation (to gather airflow usually from behind the propulsor). All of these items require some sort of actuation and could all be controlled manually. The scoops and the tee chest (ballonet air distribution) are usually situated within, or attached to the gondola, and could therefore use electrical actuators. The air and helium valves are situated on the envelope and, as with the control surface actuation, if they were to depend on electrical actuation would require power cables - with their associated weight and lightning strike complexities. Pneumatically powered actuators are a reasonable alternative to both manual and electrical actuation.

Ballast

Again the ballast dump system will require some sort of actuation. This could be manual, electrical or pneumatic. In a manual system, in addition to the cables, a weight allowance will be needed for operation handles. Both electric and pneumatic operation, while requiring actuators, can make do with simple switches.

Electrical and Avionics Group

Electrical

The weight of the electrical group will, like all systems, depend on what is required of it. For the purpose of this brief analysis, the electrical system is divided into:

- Generation system.
- Distribution system.
- Emergency electrical equipment.
- Miscellaneous.

Generation System.

When considering the weight of the electrical power generation system, there are many factors that need to be taken into account. Firstly, there is the type of power required - a.c. or d.c. How is the generation system driven, by main engines alone or with an APU, etc.? How much power will be required by the ship and how much for the mission system? Also during what phases of the flight will this be required? One other factor to be considered is the fuel usage required for this power generation.

In order to try and simplify preliminary weight estimates, we will relate weight to the power generation capacity (in terms of kVA). In terms of weight, the larger the generators the more efficient they become. For greater power requirements, however, it may become necessary for an APU to provide some of the power, thereby increasing installed weight. Any weights given below for the generation system are for the generators alone and any directly associated equipment (controllers, cooling, etc.). Based on generators being driven by the propulsion engines only, the weight will range from 2.3 kg per kVA - for something like 2 x 10kVA at the lower power requirements - down to 0.875 kg at the higher (350+ kVA for example) requirements. If some of this power will be provided through an APU, then these figures could increase by over 50%-75%

Distribution System

This is considered to consist of wiring, distribution hardware, CB panels, etc.

For the purpose of this exercise, the wiring is split into power cables and distribution wiring. Obviously, the wiring weight depends on the location of the generations system and the systems requiring the power. It is assumed, again for simplicity, that all the generation and most of the distribution are located in the gondola.

Relating the power wiring to the power requirements, the cable weight should be between 1.2kg and 1.6kg per kVA; again the higher the power the more efficient the system becomes (i.e. 1.2kg would be the figure to use for higher electrical powers). For distribution wiring, assuming no special requirements, a figure of 5.5kg per metre length of gondola cabin can be used (length includes flight-deck and equipment bays but not propulsion area). This obviously will increase substantially if there is much electronics to be supplied.

The weight of the remainder of the distribution system, CB panels, etc. is more risky to estimate in such a manner, but an allowance between 90kg for small airships and 350 kg for large airships should be made.

The above weights relate to a 'complex' airship design. Small, less complex designs, such as may be required for advertising, etc. would be expected to be considerably lighter.

Emergency Electrical Equipment.

The electrical emergency equipment will depend not only on requirements but also on the configuration and degree of redundancy in the electrical system design. Emergency power requirements will include ballonet fans (to ensure envelope pressurisation is not lost), flight control system, electrical lighting, etc. Certifying authorities attitudes must also be taken into account - whether they insist on total generation failure or double engine failure, etc. For example with generation supplied from main engines and an APU total loss of power is extremely unlikely and therefore additional electrical power supplies may not be required. If, however, generation is only supplied by main engines then total engine failure and therefore loss of electrical power will have to be considered. In this case an additional power supply such as batteries will have to be provided. The sizing of the batteries will depend on requirements such as powering ballonet fans from a height. As batteries are extremely heavy, their use should be kept to a minimum.

Miscellaneous Electrical Equipment

Miscellaneous electrical equipment would include lighting, power supplies for ancillary equipment (such as galley equipment) etc. This is hard to estimate without knowing the exact requirements. As it tends to be only a small part of the electrical system weight, however, it is not worth spending a great deal of effort estimating the weight.

Avionics

This section is intended for ship's avionics only and not for any additional mission specific equipment. Because much of the ship's avionics will be standard aircraft items, it is recommended that actual weights are used where possible. These can easily be obtained, either from the reference books available such as Jane's or from the manufacturers direct. The only area where caution may be needed is the location of aerials and radar heads.

Ballast Group

Ballast is a very important component of airship design and operation - almost a necessary evil.

Ballast Requirements

There are three possible reasons for carrying ballast on an airship. The first reason is the potential requirement for ballast to offset design balance deficiencies. Assuming an airship is designed with the gondola positioned by estimated weights to give a certain CG position relative to the centre of buoyancy (CB). If the tail structure, when manufactured, is overweight by 50kg and the tail is located 30m aft of the CB then there would be an unwanted moment about the CB of 1,500kg.m equivalent to a rearward CG shift of 0.17m at an operational weight of 8,800kg. If action was not taken, then the ship, at normal operation conditions, would be substantially out of trim and, therefore, would be limited in its performance or capabilities. One alternative is to reposition the gondola. This, however, would be almost certainly too late as by this stage most components would have been manufactured or procured. The only practical course of action would be to add a suitable amount of ballast at a practical location; obviously the greater the moment arm the smaller the quantity of ballast would be required. In the above example, if the ballast could be located on the nose (which was 27 m forward of the CB) then 55kg of ballast would be required. This ballast is dead weight because it reduces the amount available for payload, etc.

Ballast will also be carried to keep the airship at the required heaviness range. For example, an airship with 2,500 kg of available lift but carrying only 1,800kg of payload, etc. has surplus lift of 700kg - or alternatively is statically light by 700kg. The airship can either reduce lift by venting helium, an expensive and impractical practice, or carry ballast. It is, therefore,, important that suitable stowage is provided for ballast. This stowage should be as close as possible to the payload in location to keep variations in trim conditions as small as possible.

Finally, it is extremely likely that the airship will have a requirement to reduce its static heaviness quickly, especially during emergencies such as loss of engine power. One possible method is to dump fuel, but this is not always either acceptable or practical. Where fuel dump cannot be used, then a suitable amount of jettisonable ballast should be carried. For ballast, which may be jettisoned relatively regularly, it is preferable that the ballast is water. In cases of emergency, however, it may be acceptable for shot to be used. If ballast is already being carried to trim out design deficiencies, see above, it makes sense for this ballast to be disposable. Whatever form any disposable ballast takes, weights for the following items - as well as for the ballast itself -must be allowed for:

- Storage. Whether water tanks or space for shot storage, some sort of structural allowance must be made. In addition there may be requirements for sensors to measure and display content, possible heaters in the case of water and for larger airships with multiple ballast tanks some sort of method to move ballast between tanks.

- Jettison. The jettisoning of any ballast must not cause any risk to the airship.

- Jettison actuation. Some sort of jettison mechanism will be required which may be actuated manually using cables or via some sort of powered actuation, e.g. pneumatic, electric, etc.

Underway Ballast Replenishment

There will be requirements, on some projects, for additional ballast to be taken on board during flights. A simple illustration is as follows. As fuel is used, the ship will become lighter. It may then become necessary to replace the weight of the used-up fuel with ballast.

There are two main methods of doing this (though additional water could also be collected relatively simply and for very little weight from the envelope). One method is to pick up water or other ballast from the surface. This could form part of an underway replenishment (Unrep) system. An alternative method is to fit a water recovery system. This condenses the moisture suspended in the engine exhaust. Ballast pick-up will require the airship to be very close to the surface for some period whilst water recovery could be carried through many stages of the operation.

Thought must be given to storage of the additional ballast, whichever method is employed.

Water Recovery System

A water recovery system could be used to condense the moisture suspended in the engine exhaust. It must be emphasised that water recovery is more suited to reciprocating, rather than turbine, engines. Although it would not be impossible to have water recovery from a turbine engine, its efficiency would be low. Realistically, however, this would be impractical. Theoretically, it should be possible to retrieve 1kg of condensate for every kilogram of fuel burned, making it ideal for keeping to the required ship heaviness. However, this can be complex, heavy and require a considerable amount of power. For large airships (with main engine power of over 3,000 h.p.), an allowance of 0.75 kg/h.p. should be made. Insufficient work has been carried out to date to determine an allowance accurately for smaller engine sizes. Such values are, therefore, not presented here - though it must be considered impractical for smaller airships. With reference to water recovery systems, it would be wise to consider the following additional factors:

- ***Volume***: Designs currently proposed for water recovery systems indicate that they would occupy a considerable amount of space. Additionally, they would tend to have large frontal areas for cooling.
- ***Power Requirements:*** The power requirements, and type, of the power supply need to be considered. Power supply would be required by equipment such as condensers and fans.
- ***Pipe-work***.
- ***Controls***.

Pneumatic and Hydraulic Systems

Pneumatics

Pneumatic power can be, and currently is being, used as an alternative power supply. Many control applications, requiring actuators, can use pneumatic or electrical power. Additionally, air can be supplied for other uses such as engine starting. Pneumatic power could either be supplied from compressors or from high pressure air storage. Stored air alone gives a finite amount of power, which limits the effectiveness of the power source. As far as weights are concerned, there are, as might be expected, both advantages and disadvantages. Pneumatic power is heavier to produce. Assuming that some sort of generation capability is required (rather than pure storage only), then compressors, dryers/filters, reservoirs, control valves, etc. will be required. Distribution, especially to the envelope, is considerably lighter and has other design and operational benefits such as low maintenance and reduced metal content.

Hydraulics

Hydraulic power, like pneumatics, is another suitable power source. It is more limited, however, owing to problems resulting from the hydraulic fluid itself. Also, because of possible reactions with envelope fabrics, it is not really suitable for pumping around. Further, the weight of the hydraulic fluid could have a significant effect and must be accounted for. Hydraulic power should realistically be considered, with current technology, as being suitable for higher power applications.

Other Items

These are a group of items which can all too easily be omitted or underestimated when deriving the airship operational weight. They are not strictly part of the M.E.W. and, probably, would not be considered as part of the payload.

Standard Items

Standard items are defined as equipment and fluids that are not an integral part of a particular airship configuration. They are also not a variation for the same configuration. These items include:

- Unusable fuel and other unusable fluids.
- Engine oil.
- Fixed Ballast.
- Toilet fluid and chemical.
- Airship emergency equipment.

- Galley structure, etc.
- Supplementary electronic and avionics equipment (for a particular configuration).
- Fixed mission equipment and armament not included in MEW.

The first two items are part of the airship, though not part of the MEW, and their weight must be deducted from that available for payload. The remainder are usually dependent on the mission and, therefore, also dependent on the payload. They will even usually not be considered with the payload, but the necessary allowances must be made.

Payload/Mission Equipment

As already mentioned above, when considering the payload, there are many factors to be taken into account other than the explicitly stated items.

Civil payloads will be primarily passenger carrying, although there will always be proposals for specific applications such as logging or bulk gas carrying - these applications are too specialised to be covered here. Passenger carrying flights will obviously require seating. The type and number of seats need to be considered. For example, a luxury seat (as might be fitted to a business jet) can easily weigh 3 times the weight of a standard high density aircraft seat. Carpets, or an alternative floor covering, will almost certainly be fitted as well as decorative wall coverings. Other facilities, such as catering and toilets, will depend on the type and endurance of the flight. Provision for hot food and drinks adds a considerable amount of weight when compared to simple storage for sandwiches, etc. The same goes for toilet facilities. While a curtain and chemi-loo might suffice for military style operations, it is unlikely to be suitable for fare paying passengers. A suitable toilet installation in this case is likely to include a vanity unit, sink, mirrors etc and will require an adequate amount of water and toilet fluid. One other consideration is the possible requirement, through aviation regulations, for cabin crew.

Requirements for an explicit military or para-military fit could add a considerable amount of weight. Whenever possible, a complete list should be obtained - if not of actual equipment, then of the requirements, e.g. how many communications channels and of what sort (VHF, UHF, secure, etc.). Further information on military and para-military items is given earlier in this chapter.

Operational Items

A definition of items comprising the operational items can be found above. Again, these can easily be omitted when determining the lift for the available mission. It is important to make allowances for food and water for crew and passengers, especially for the longer endurance flights.

WEIGHT MONITORING AND CONTROL

Controlling the weight of an airship is a difficult task during the design and building stages. This is in common with many small or specialised aircraft where resources are tight and planned production runs are small. Again, it should be emphasised that the weight must be tightly controlled, because any overweight can have a serious effect on the airship's capabilities, possibly limiting its feasibility. A 5% increase in airship empty weight could easily lead to a reduction in payload of 20-25%!

The prototype methods of design and construction will almost certainly introduce cheaper heavier commercial components rather than aerospace quality items into the design. This must be avoided where possible. In fact, an airship is a good platform for prototype components.

BUILD WEIGHT CONTROL AND ACTUAL AIRSHIP WEIGHT DETERMINATION

Introduction

Whilst it is necessary to know accurately the weight and CG of a complete and inflated airship, it is practically impossible to measure it physically. The actual weight of the airship can only be obtained by weighing all the components while the airship is being built. As a check, a hangar weigh-off could be carried out in as near perfect conditions as possible. Similarly, the actual volume of the envelope, and therefore the gross lift, cannot be practically measured accurately.

Build Weight Control

The build weight control is a vital operation in the life of an airship; it defines the Bare Empty Weight and is the fixed point for any modifications during the ship's life. It is not enough that the items are weighed and recorded, it is also vital to know the build standard of each item. The build weight of the airship can be divided into three groups. Firstly there is the gondola weight prior to attachment to the envelope, secondly there is the hull group weight and finally the assembly and final build weights.

Gondola Weight (Conventional suspended gondola).

The gondola, when complete, will be a typical complicated aircraft mix of structure and systems. The gondola can be weighed conventionally throughout it's build and before attachment to the inflated envelope. This should be done many times. Again, it is not enough just to know what the weight of the gondola is, it is also necessary to know what the build standard is (i.e. what is fitted, what modifications are included, any omissions, etc). Without these data the weight is virtually useless.

The starting point for the build-up of the gondola weight will be the shell or structure. This should occur as close to completion as possible but, as far as possible, without fitting any systems or ancillary structure. The build standard should be carefully noted (i.e. the revisions of the drawings and any omissions or additions). Unless the airship is in a lengthy production run - which is unlikely - this should be done for every gondola. This is because differences between the gondolas can be substantial, especially for composite construction.

Because the gondola will be mounted in some sort of support trolley or jig, data and weighing procedures must be well established and used.

Hull Weight

The envelope must be weighed and, like everything else, its build standard at the time of weighing must be accurately determined and weighed. All the fitments, patches, lines, etc. must be weighed as fitted, to determine the hull weight.

It is impracticable for the envelope to be weighed inflated, so it must be weighed deflated. This is acceptable for weight but is no use in deriving the CG of the envelope. The latter can only be assessed through measurement after build, at which time an approximate check of the envelope volume can also be made. A check can be made through a hangar weigh-off and a climb to pressure height. These are discussed in slightly more detail later.

Final Assembly Weights

Once the gondola is attached to the envelope, it will not be possible to weigh the vehicle again. It is, therefore, extremely important to weigh and record every item or material fitted to, or removed from, the airship. This must be undertaken with the strictest discipline.

Hangar Weigh-off

A hangar weigh-off is usually undertaken immediately after completion of build. If the weight has been monitored carefully then, with comprehensive measurement, a good assessment of the lift capabilities of the airship can be made. Even if it is not realistic to have the highest level of confidence in the derived weight, it is still possible, with some care, to carry out a check on the weight. In order to perform the weigh-off, the following steps should be taken and data recorded or derived. Use of a properly designed load-sheet will greatly help this process.

- Derivation of the operational weight of the airship. The basic weight should be obtained from the Weight & Balance document, to which will be added the crew, fuel, disposable ballast and any other items that are onboard the airship.

Great care must be taken to ensure the airship is to the build standard indicated in the Weight & Balance manual, any deviations being recorded.

- The airship should be brought to equilibrium by the addition or removal of ballast. The amount of ballast altered should be recorded.

- The airship should be trimmed using any suitable disposable ballast repositioning (e.g. nose to tail) and by ballonet trimming.

- The helium properties (purity and, if possible, volume, internal pressure differential and superheat), local atmospheric properties (temperature, barometric pressure, relative humidity, etc.) and the ballonet fill should all be recorded.

- The net gas lift should be determined.

- As the airship is at equilibrium, the weight should be equal to the lift.

The main areas where error could be introduced are the envelope and ballonet volumes. The envelope volume can, to a certain extent, be determined by physical measurement. The ballonets volumes are much more difficult to determine. A method of improving the level of confidence is to carry out calibration flight. One note of caution, the envelope will almost certainly increase in volume during the first several months of operation before settling down.

Envelope and Ballonet Calibration

To check the envelope volume, a flight to pressure height can be made. This should be attempted in calm and dry weather to reduce the effects from moisture, turbulence, etc. Again, as this is dependent on accurate weights, a load-sheet should be accurately filled out before the flight. At pressure height, an assessment of the static heaviness should be made. As the ballonets will now be flat, a major variable is taken out of the equation and a more accurate assessment of the lift can be made.

By levelling off at pre-determined altitudes, both during the ascent and descent, it is possible to make calibration charts for the ballonets by measuring the ballonet`s fills and calculating the lift.

WEIGHTS ASPECTS OF AIRSHIP OPERATIONS

Introduction

This section is not concerned with airship lifting performance. What it aims to do is highlight areas where there is some sort of weight, or weight related, input.

Like any aircraft, an airship should be flown, or operated, within certain limits. These limits will include weight and balance or trim criteria, and could include some or all of the following:

- ***Maximum Design Operating Weight:*** This is the maximum weight at which the airship can be flown (refer to the first section of this chapter for definitions). This will have been set early in the design process allowing stress and aerodynamic calculations to proceed.

- ***Centre of Gravity Envelope:*** This allows the derivation of acceptable CGs for the range of weights at which the airship can be operated. Because of the inherently wide trimming ability from the ballonets, this can be much more flexible than for a fixed wing aircraft. It has its own dangers, however, in that the correct trim can only be maintained as long as neither ballonet is flat. As soon as the airship rises beyond that point, it will become out of trim.

- ***Maximum Design Suspended Weight***: This, in many cases, could be more important than the Maximum Design Operating Weight, because the suspension system will be designed to this figure.

- ***Maximum Suspended Weight Moment:*** In order to stress the suspension system, the CG range at which the suspended weights are acting is also required.

- ***Maximum Static Heaviness and Lightness***.

It is very important, therefore, that there is some method of ensuring that these criteria are not exceeded during operation. A load-sheet completed by the pilots before flight - using weight and balance data contained within some sort of weight handbook - should be used. This is standard aircraft practice and, although there are additional complexities for airships, it should be acceptable to aircraft pilots and operators.

Weight and Balance Handbook

This document should contain weights and associated CGs for the empty airship and for all the mission fits and operational items that may be fitted to the airship. An airship is likely to have a considerable number of configurations; it is important to be able to derive accurately and quickly the airship weight and CG for any configuration, without resorting to the design offices. Any new equipment or revisions to existing equipment should be reflected in the handbook. Any CG envelopes should also form part of this document.

Load-sheet

The load-sheet should be completed by the pilot before flight. Its purpose is to ensure that the aircraft is loaded such that it will be within operational and design limits throughout all stages of the flight. A correctly designed load-sheet should be able to address most, if not all, of the following points.

- Easy input of start data - airship Basic Empty Weight and Basic Suspended Empty Weight and associated CGs or moments.
- Easy addition of variables such as passengers, fuel, disposable ballast, etc. to derive airship Operational Weight and Operational Suspended Weight.
- Determine quickly that these derived weights are within limits.
- Show trim condition of the airship (with neutral ballonet fills).
- Show required ballonet fills necessary to bring the airship into the required trim condition.
- Allow estimation of heaviness condition at take-off, landing and worst *en-route* stages.
- Allow approximate estimate of available lift to be made for comparison with previous flights.
- Determine the amount of disposable ballast carried, and whether enough is being carried to bring the airship to the required heaviness condition in case of emergency.

Because of the amount of information that has to be presented, it is important that the load-sheet be kept as clear as possible, with minimum use of written and calculated data and maximum use of graphical information. Providing details of producing and using load-sheets is, however, beyond the scope of this chapter.

10

Systems

N. Mayer

INTRODUCTION

Systems are the physical means of achieving a designed function. They consist of components, control mechanisms, and sensors. Some systems are essential to the operation of others, such as those that are power sources, examples being electrical, hydraulic, and pneumatic. Airship systems include most of the major and minor groups found on all aircraft and a few that are peculiar to lighter-than-air aircraft.

The systems described can be found on most airships but the design, complexity, and location may differ considerably from type to type. Some systems may be peculiar to airships designed for particular missions, such as an inflight replenishing in military applications. Some major systems not covered in this chapter include flight control and propulsion, since they are described elsewhere (Chapters 4 and. 5).

Emphasis is placed on non-rigid airships since all currently in operation are of this type and for this reason pressure systems receive the lengthiest description. Many other airship classes also rely on pressurised hulls or envelopes to achieve structural integrity such as semi-rigids, pressure-rigids (metal-clads) and hence all require pressure control systems in one form or another.

Particular designs have been chosen as representative of the state of the art. Certain past airships that included features worth mentioning - not found in current designs - are also described.

PRESSURE CONTROL

The pressure control system is so named because the superpressure of the lifting gas is the primary parameter sensed in the function of the system. However, the system involves many elements, most of which are connected with the intake, distribution, storage, and disposal of large quantities of air required to compensate for changes in gas volume.

Density of the lifting gas varies in accordance with Boyle's and Charles's laws. Since gas pressures are kept within relatively narrow limits, the variations manifest themselves primarily as volume changes. Airships must maintain a fixed exterior geometry, hence volume adjustments must be accommodated internally. This is achieved by keeping a variable quantity of air within the envelope so that air and not lifting gas is discharged or added. It should be noted that many of the so-called barrage balloons used during World War II actually did vary their exterior shapes while maintaining an aerodynamic form.

A system, used on certain historic semi-rigid airships, incorporated an air barrier between the outer envelope and the gas cells. As the cells expanded or contracted the surrounding air volume changed to compensate (Blakemore and Pagon, 1927). This system had the advantage of requiring only an air tight outer hull or envelope and also allowed the airship to reach altitudes not limited by ballonet size. Disadvantages included the complexity of an outer and inner envelope or gas cells, suspension system compromises, and higher construction and erection costs.

Current airships all favour the ballonet system. This utilises one or more flexible air cells located in the lower part of the envelope. These are emptied or filled with air as the lifting gas volume changes. This principle is illustrated in Figure 10.1.

The size of the ballonets and the rest of the pressure system are determined by the maximum pressure height and by the rates of ascent and descent that he airship is designed to achieve. Ballonet capacity is determined by the density ratio between sea level and the maximum pressure height. Volume change rates are determined by the following equation (Burgess, 1927):

$$V = \frac{R\,d\cancel{V}}{60 \times 1000} \tag{10.1}$$

where:

V = Volume change - cu.ft./sec.
R = Climb or dive rate - ft/.min.
d = Density change
$\cancel{V}$ = Envelope volume - cu.ft.

As an example, a one million cu./ft. airship, climbing at a rate of 2,500 ft/min will have to discharge 33 000 cu.ft. of air during the first 1000 feet of altitude change in 24 seconds.

Similar considerations apply to all airships, regardless of how changes in gas volume are managed. Rigids, for example, must regulate gas cell superpressures by valving. Also, adequate venting of the outer cover must occur to keep this air space pressure close to ambient. Hybrid types, such as pressure-rigids (metalclads or the more recent Zeppelin NT concept) must employ a type of ballonet system.

Air is replenished or removed from ballonets through a combination of scoops, ducts, and valves. While large volumes may be required, the superpressures are low, values being in the order of 0.1 p.s.i. Air intakes must be of sufficient size to furnish the quantities and rates required without significant friction losses. A flow rate of 50 ft^3./sec. or less is recommended.

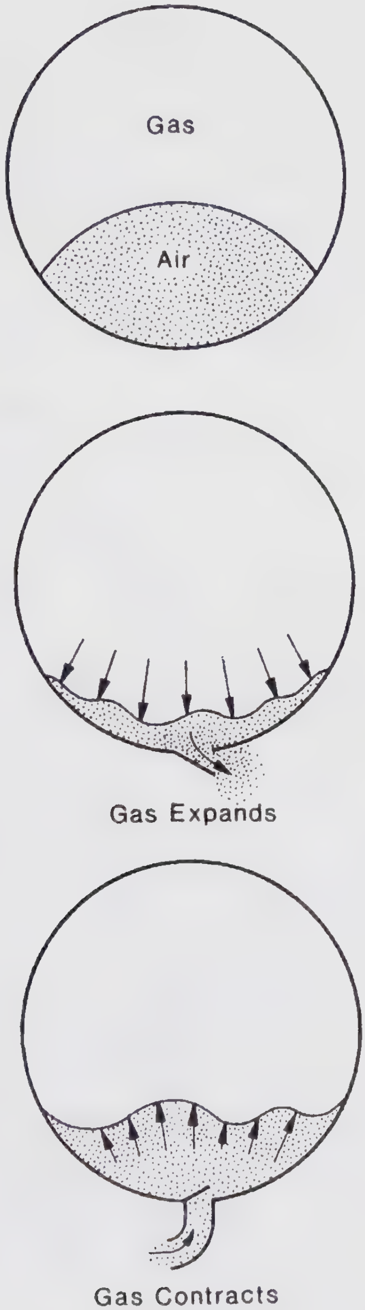


Figure 10.1. Pressure and shape control principle of the ballonet.

Ram air, augmented by propeller slipstream, is the primary source for air intake. Scoops are located behind propellers. At low airspeeds, electrically powered blowers can be used. A single fan is sufficient for small airships, while multiple blowers are required for larger ships. Capacities are determined according to specifications. On the Westinghouse Sentinel 1000, a 353,146 cu.ft. airship, two fans provide a descent rate of 1200 ft./min. A projected design, the Sentinel 5000, a 2.5 million cu. ft. airship, requires four blowers to achieve a specified descent of 600 feet per minute.

In some multi-engine airships, where the engines or propellers are supported on outriggers and tractor propulsion is used, the leading edges of the outriggers are convenient places for locating the intake ports. This method is employed on German airships built by WDL Luftschiffgesellschaft mbH and was also used on U.S. Navy airships built by Goodyear Aerospace. Airships with ducted propellers and those with pusher propulsion require aft mounted scoops.

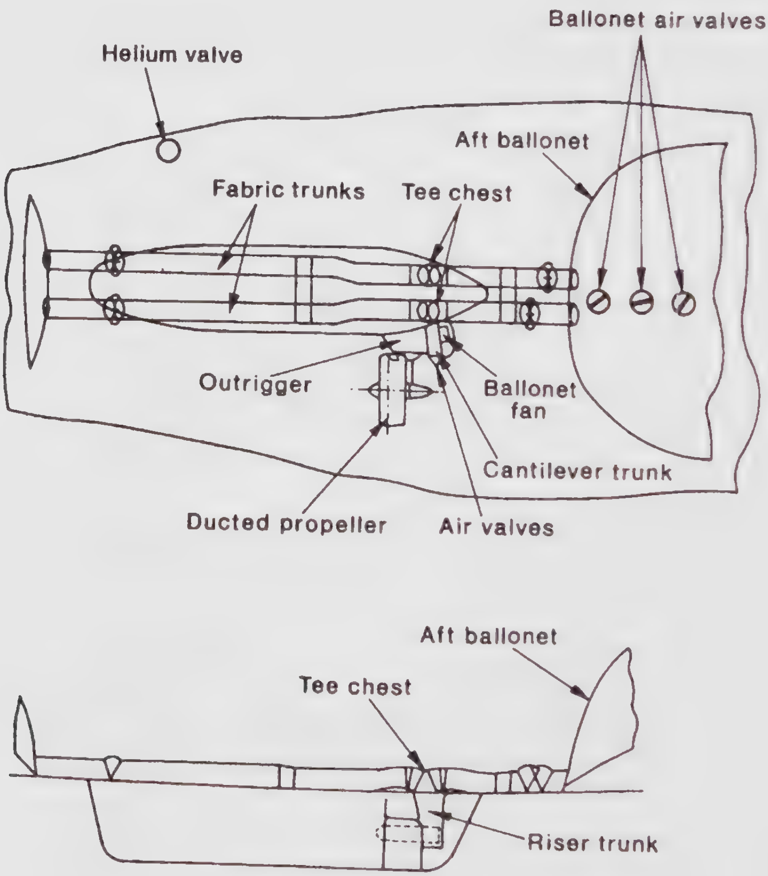


Figure 10.2. Ballonet air supply trunking system (Sentinel 1000).

Flapper-like check valves mounted in the air intake passages are spring loaded devices which prevent reverse flow. Air is directed to one or more chambers or plenums and thence to the ballonets through long fabric ducts. Dampers of single or double flap design, controlled by the pilot, are used to select the ballonets to be filled. Current designs use twin ducts, either of which can channel air to forward or aft ballonets according to the damper setting. The ducts, also referred to as trunks or air lines, are channels only for air intake in current designs. Air discharge is accomplished through valves mounted directly under the ballonets. In U.S. Navy airships, the air lines provided for both intake and exhaust functions.

Figure 10.2 illustrates the air supply ducting for the Sentinel 1000 airship. Figure 10.3 shows the arrangement for the Sentinel 5000, which is equipped with centre ballonets. A typical central distribution chamber (Tee chest) is shown in Figure 10.4.

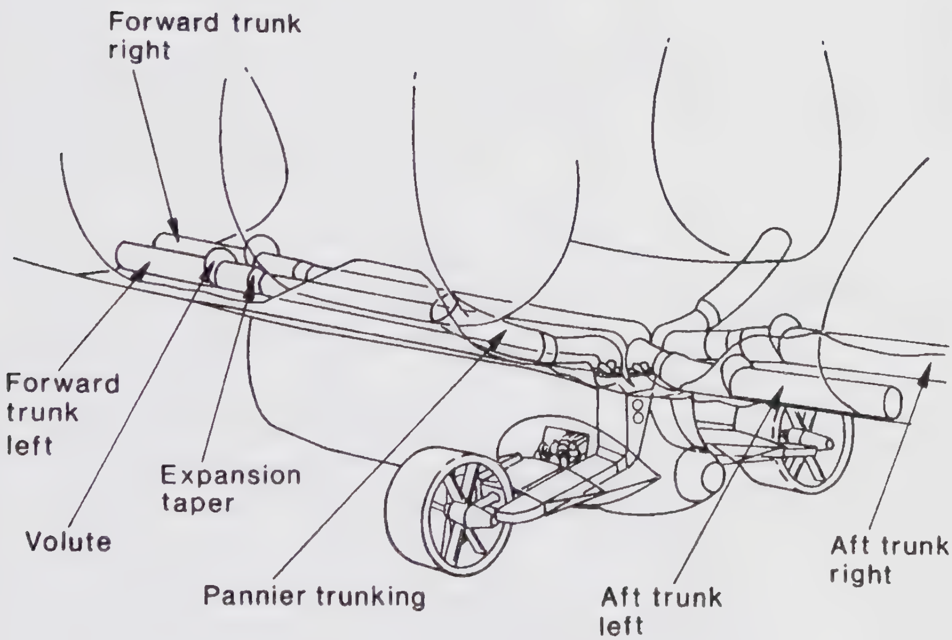


Figure 10.3. Envelope fabric structure – ballonet trunking (Sentinel 5 000).

Large diameter valves are required to achieve the necessary flow rates. The valve opening area can be expressed by the following equation (Blakemore and Pagon, 1927):

$$A = \frac{V}{c\sqrt{2p/\rho}} \tag{10.2}$$

where:

A = Opening area

c = A discharge coefficient determined from tests. (Current designs achieve 0.75).

ρ = density (slugs)

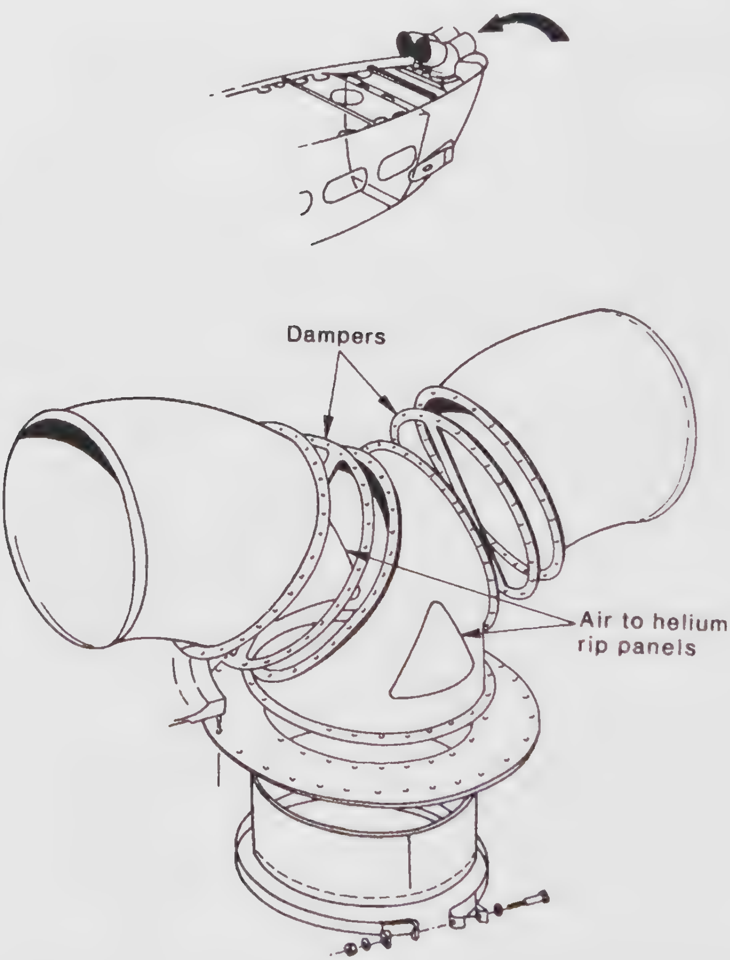


Figure 10.4. Tee chest (exploded view) (Sentinel 1000).

Very small airships may require a single valve under each ballonet. Although valves can be built in any size, it is more practical to use multiple installations. Presently, diameters of individual valves used in Westinghouse airships vary between 20 and 42 inches. The bottom surface of the ballonet, which is the envelope, is the location for mounting air valves. Gas valves are located on the side of the envelope in the vicinity of the equator. Past U.S. Navy airships were equipped with two or more 36-inch diameter air valves mounted in the upper part of the car. This allowed easy maintenance and protection against the effects of weather (hence the need for two-way flow air lines). In the ZPG-3W, a 1.5 million cu.ft. AEW airship, helium valves were also located in the car.

Valve opening pressures are set at various and different values to allow valves to function sequentially. In a two ballonet airship, it is customary to set either the forward or aft valve as the lower to allow for continuous air circulation without disturbing trim during level flight. Airships equipped with centre ballonets can be trimmed with the forward and aft cells and maintain pressure using the centre ballonets.

Reliable valve functioning is essential for the proper performance of the pressure system. Valves are designed to open automatically when air or gas pressures exceed the valve setting. A spring and lever mechanism is employed to allow the valve to open fully and quickly without further increase in pressure and to pop closed when the pressure drops. The structure of the valve must be rigid enough to eliminate warpage or misalignment, which would result in leakage. A drawing of the valve used in the Sentinel 1000 is shown in Figure 10.5.

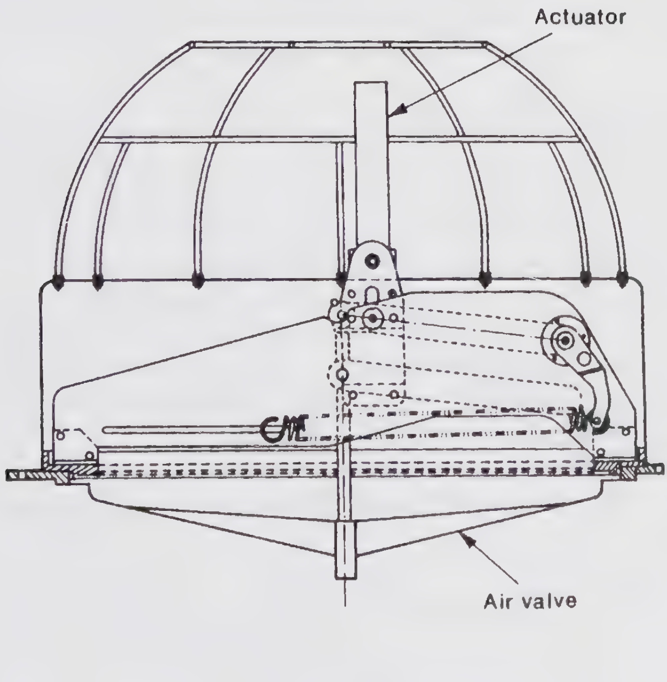


Figure 10.5. Ballonet air valve details (Sentinel 1000).

Manual operation is also provided so as to allow a valve to be opened or locked closed by the pilot when certain operating conditions are desired. This is accomplished through cable connections or, in the case of the Sentinel 1000, by pneumatic actuators. The pneumatic system also serves to operate dampers and scoops. Electrically powered components were installed in some past U.S. Navy airships.

Externally mounted valves are subject to the effects of reduced static pressures owing to air flow around the envelope. This can cause the valve to open at lower pressures. Air dams, in the shape of semicircular fences, may be installed to counter these effects.

The number of ballonets depends to some extent on the size of the airship but other factors also have an influence. One of these is the movement of air in a partially inflated ballonet. This movement, known as sloshing, has an effect on control and trim. Ballonets must also inflate and deflate without interfering with, or being interfered by, other internal components such as the suspension system. These considerations usually dictate a minimum of two ballonets. Two ballonets also allow a convenient means of trimming the airship when they are located forward and aft of the car. Past U.S. Navy ZPG series airships and the projected Sentinel 5000 were designed with forward, aft, and centre ballonets. The centre cells, also called panniers, are located on either side of the envelope near the centre of gravity where volume changes have no effect on trim. This arrangement also lends itself well to the design of automatic pressure control. Single ballonet design is used in the American Blimp Corporation Light-ship. This is a small 68 000 cu.ft. airship with no internal suspension system.

Ballonets are constructed of elastomer coated nylon or with a laminate of film, such as Saran or Mylar, and nylon or polyester cloth. Materials are chosen for flexibility and air retention. Although average stresses are low, sloshing and volume changes cause concentrations at base seams and at air line intersections. Provision has to be made for these effects by reinforcing and by adding expandable sections.

An improved design for ballonet shape has been incorporated in Westinghouse airships. This employs a longer base dimension and geodesic patterning, which eliminates any mismatch between the ballonet area and the envelope surface over which it is located. This design, shown in Figure 10.6, allows stress-free nesting, reduces sloshing, is lighter, and more efficient to manufacture.

Another component of the pressure system is an air-to-helium sleeve or rip panel, which allows air to be blown directly into the helium in an emergency (see also *Emergency Systems).*

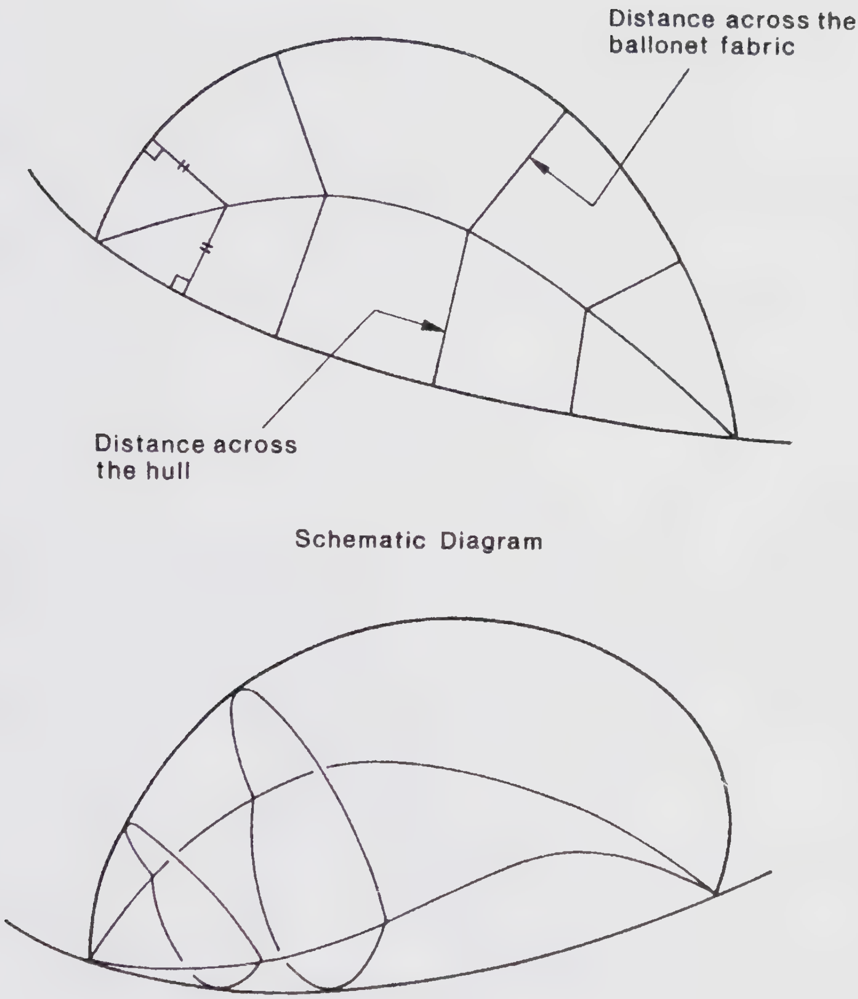


Figure 10.6. Ballonet design – geodesic method.

FUEL

Fuel Systems consist of storage tanks and transfer lines to the engines with the necessary selector and shut-off valves and controls, and provisions for draining or dropping fuel. As in most aircraft, it is important to locate fuel tanks where minimum effect on trim will occur as the fuel is burned. Airships offer ample opportunity to meet this requirement since their large dimensions allow many choices for tank locations. Design philosophy varies considerably. A small airship may need only a single tank located in the car near the engine(s). Large quantity storage must be distributed among several tanks. The U.S. Navy ZPG-3W was equipped with two 1,150 gallon (U.S.) tanks suspended on long cables from the top of the envelope and located forward and aft of the car. Seven other tanks were located in the car. Five of these were slip tanks, i.e., the entire tank and its contents could be released in an emergency. One tank served as a combination fuel and ballast storage container. The system was designed to feed all fuel to a service tank from which it was pumped to the engines. By selective usage, minimum trim effects were achieved.

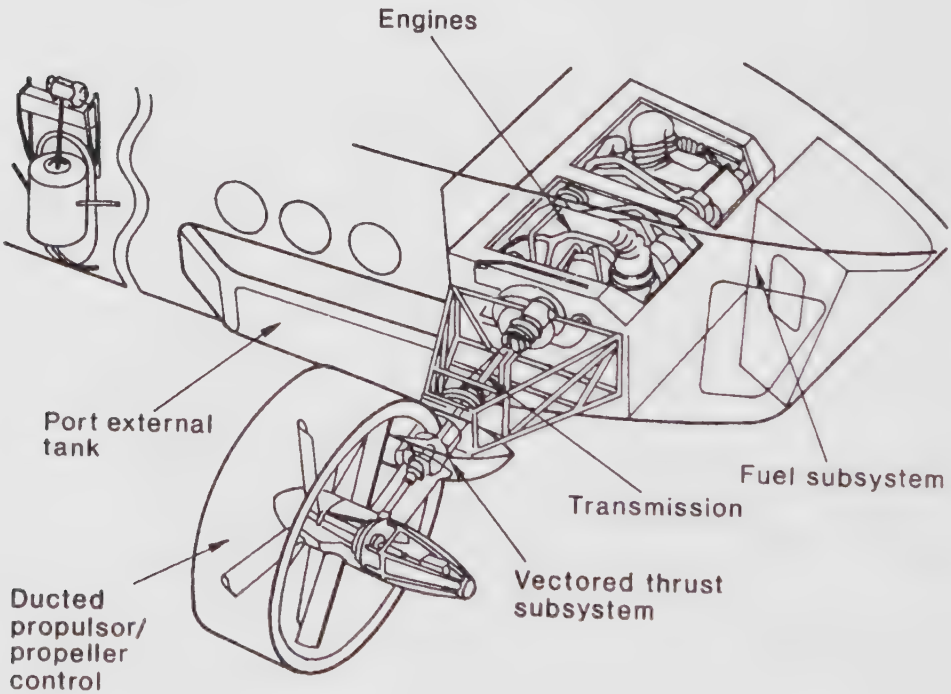


Figure 10.7a. Fuel system layout - Sentinel 1000.

A different arrangement is planned for the Sentinel 5000. In this design, all fuel is located in fixed tanks arranged in a vertical manner in the car on either side of the cargo bay, which is close to the airship's centre of gravity. Rapid draining is provided for emergencies.

The fuel system's layout for the Sentinel 1000 is shown in Figure 10.7. The original design, used also on the smaller, earlier Skyships 500 and 600, included one main tank holding 168 gallon (U.S.). Increased endurance on the Sentinel 1000 is obtained by the installation of two external tanks on either side of the car. An experimental fuel pick-up system is also shown. German WDL airships are equipped with two fuel tanks suspended on the car support cables within a centre ballonet in the envelope.

Externally mounted tanks are often used on airships when extended range or endurance is needed. U.S. Navy ZPG-2/2W airships employed four cylindrical tanks mounted on the envelope at 45 degrees from the bottom, forward and aft of the car. Two tanks per side were supported externally by short catenary curtains and cables. Each, when full, weighed 2100 lbs.

Normal aircraft standards are used in the design of airship fuel systems in terms of venting, draining, and dumping of fuel. Most systems require pressure fuelling. Since fuel can also serve as ballast, provision must be made for rapid removal. This can be done with high rate drain valves or with slip tanks, as noted. This latter method was a standard feature on all U.S. Navy airships. About 30-35% of the fuel was carried in this way.

Fuel storage tanks may vary in their construction. Bladders are used in Westinghouse airships; these are enclosed by the surrounding car structure. Aluminium and fibreglass reinforced plastics (composites) are also used. Rigid tanks are usually required to be tested and qualified by vibration and sloshing tests.

Oil reservoirs are required to provide engine lubrication. These are located near or in the engine compartment. Oil is pumped to the engines, then through a radiator for cooling, and returned to the tank.

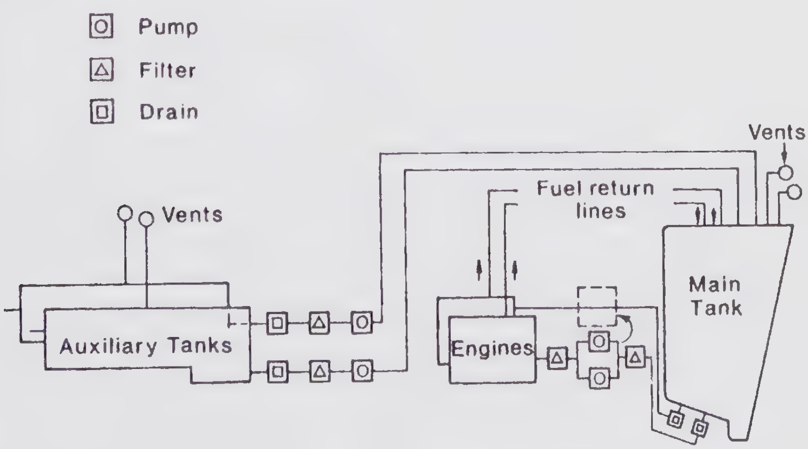


Figure 10.7b. Fuel system layout - Sentinel 1000.

BALLAST

The weight of an airship can be adjusted by ballasting. This process involves adding or removing weight carried for this purpose; fuel, water, sand or shot are the materials generally used. The discharge or release of fuel is an emergency procedure only and strictly regulated. The potential hazards involved favour the use of slip tanks, at least over water. Water is the most common ballast material. Solid materials such as sand or shot are used in small airships for fine tuning the static condition prior to take-off. These materials are stored in compartments accessible to the ground and flight crews. Water is stored in tanks or bladders.

Lift and weight are affected by environmental conditions and by changes of weight on board, such as the consumption of fuel. All of these effects can be compensated to a degree by trimming to achieve a positive or negative angle of attack. Efficient flight, however, requires maintaining pitch angles close to zero, i.e., maintaining equilibrium near to static condition. A properly designed ballast system must, therefore, allow for weight to be added or removed. One method, used in U.S. Navy non-rigid operation, utilised a fabric bag which was lowered to the sea, filled, and then hoisted aboard, the water being emptied into storage tanks. This manoeuvre not only required considerable skill from the pilot but also favourable conditions in which to carry it out.

Since water is produced as a by-product of combustion, engine exhaust gases can be cooled to recover the water, which is then used as ballast. This method has been employed successfully in the past on rigid airships. It has not been part of non-rigid ballasting systems because of complexity and weight - this latter item accounting for about five percent of the empty weight in rigids. Modern technology and newer design concepts now promise more efficient systems and these are being planned for larger non-rigids such as the Sentinel 5000.

Water recovery involves a process of cooling engine exhaust gases from high initial temperatures to condensation values. Recovery temperatures vary with the type of fuel used and the fuel:air ratio in the combustion process. The former is characterised by its hydrogen content. Altitude, ambient temperature, and relative humidity affect recovery rates. The Sentinel 5000 system is designed to operate under the average conditions of 5,000 ft. altitude, an ambient temperature of 77°F and a relative humidity of 30%. The diesel engines are assumed to operate with a fuel:air ratio of 35:1 and an exhaust gas temperature of 680°F, which will produce a quantity of water equal to the weight of fuel burned. Deviations from these values would result in more or less recovery. Initial temperature reduction would occur through a precooler and the final stage would be through a freon heat exchanger.

Heat from recovery systems can by utilised for climate control within the airship, or to create artificial superheat of the lifting gas, or be rejected. Provision must be made to protect water ballast against freezing in cold weather operations.

Exhaust water recovery systems are sensitive to maintenance problems. Gases contain corrosive compounds and usually considerable amounts of carbon (soot). Diesels produce less of this substance than petrol (gasoline) engines. Material selection in design of systems is important, as is provision for easy cleaning and maintenance.

Other ballast recovery systems have been tried experimentally, such as trailing pumps and hoses, but none has proven practical so far. The Sentinel 5000 design also incorporates rain gutters near the top of the envelope - as were used in the German Zeppelin, 'Hindenburg' - these would be connected to fabric ducts to channel collected rain water to storage tanks.

ELECTRICAL

Electric power is an essential element of most of the other systems in modern airships. During the design phase an analysis must be made of the electrical load so that the required number and size of generators, auxiliary power units, and batteries may be identified. Naturally, large airships such as those carrying radar and other surveillance equipment will require much more electrical power than smaller civil types. These needs are reflected in the amount of horsepower required to drive generators. It is not unusual that a military airship flying at slow speed in a surveillance mode would be devoting more of its engine power to furnishing electricity than is required for propulsion. Table 10.1 illustrates the significant differences for two modern airship designs:

Table 10.1. *Differences between Sentinal 1000 and 5000 airships*

	Sentinel 1000	Sentinel 5000
Envelope Volume - cu.ft.	353 146	2,500,000
Power Supply - KVA	7.8	450
Type	28V DC	115V 400Hz

Electrical systems are usually designed to be redundant for maintaining essential flight functions, hence multiple generators are installed. In normal operation, each share a portion of the load, distributing power to bus bars, then to various components and systems. The bus bars are isolated or used in parallel so that power interruption to sensitive or vital equipment is prevented should partial failures occur. Batteries provide emergency and start-up power, or this latter function may be available from a ground power unit. Generators are normally driven by the propulsion engines. Part-time power may be furnished by an auxiliary power unit.

28V DC systems are a current standard on many small airships. The Sentinel 1000 produces its power from four engine-driven generators. Two of these provide 100 amps; the other two provide 40 amps. One of each type is mounted on each of the two engines. The output is fed to an independent bus, which channels it to various systems via sub-bases. In the case of engine failure or generator malfunction, the load is transferred to the opposite engine's generators. Three 43 amp lead acid batteries provide back-up emergency power. An electrical block diagram for the airship is shown in Figure 10.8.

The Sentinel 5000, in its military configuration, utilises five 90 KVA generators, furnishing DC and 400 Hz AC power through invertors. Each generator can produce 150 KVA for short periods. Figure 10.9 illustrates the distribution and sharing of power in this design. Special mission power is supplied by an APU.

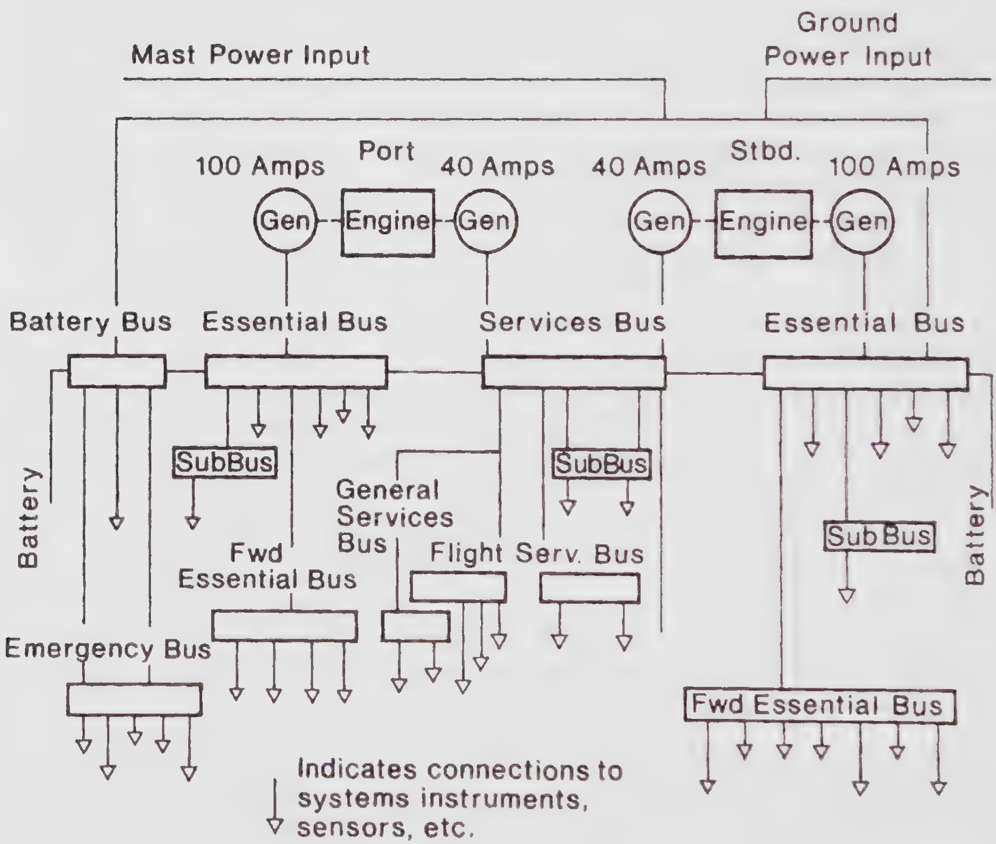


Figure 10.8. Electrical block diagram - Sentinel 1000.

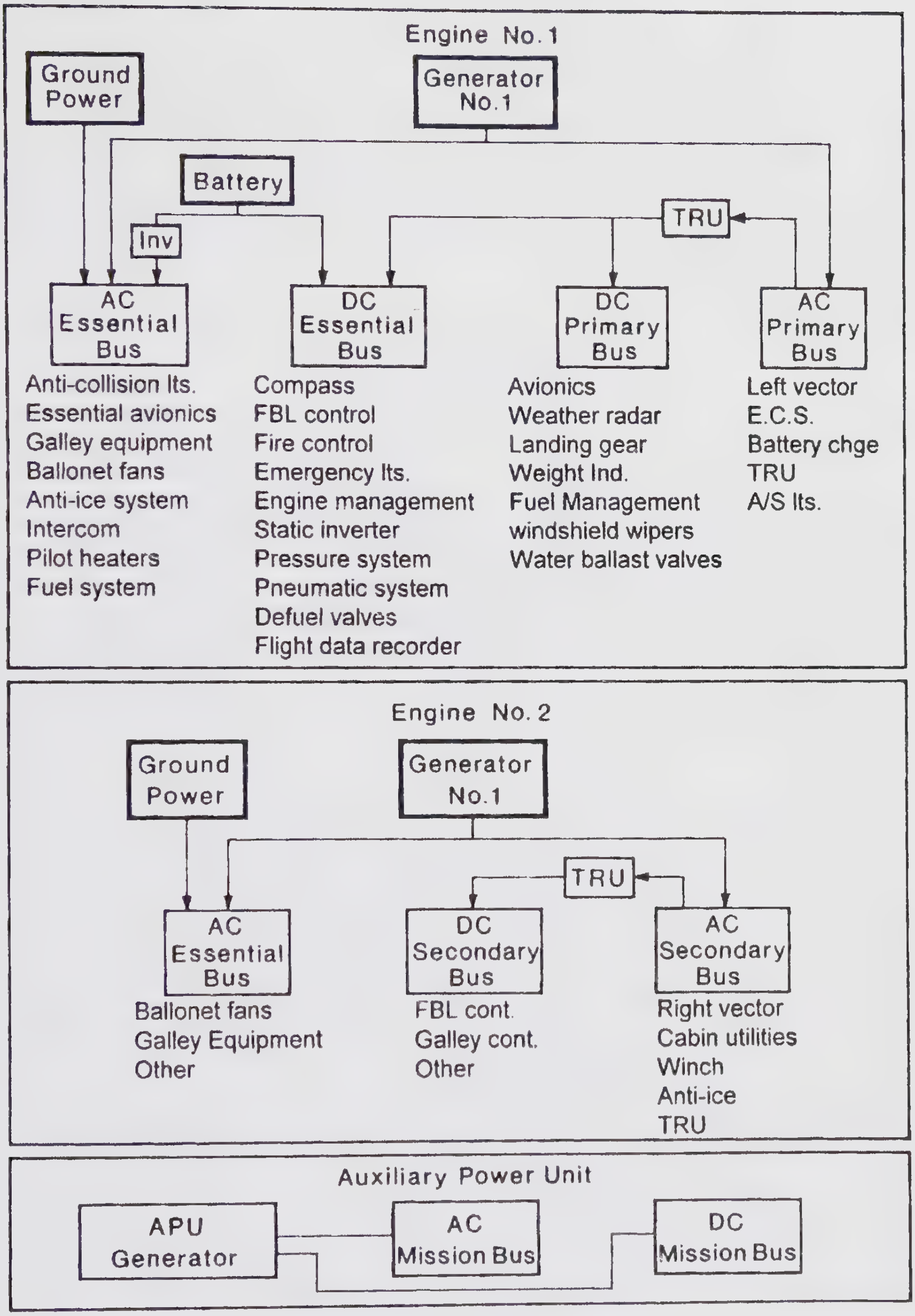


Figure 10.9. Electrical power distribution - Sentinel 5 000.

Small airships, used for advertising, may be equipped with a portable APU when power for electrically lighted signs during night operations is required. One example is a Honda powered unit which delivers 2000W at 110V mounted on the car of an American Blimp Corporation Lightship. This airship has a translucent envelope on which are attached (by patches) multi-coloured banners displaying a sponsor's message. Illumination is obtained by floodlights mounted inside the envelope. The APU is also required when television broadcasts are made.

A permanently mounted APU would be used on the Sentinel 5000 as a source of power for military mission equipment and also to function as emergency power after cutting off the military load.

It is necessary to maintain certain onboard functions when the airship is on the ground. This is usually attained by using a ground power unit.

CREW

Accommodations for personnel vary with the size of the airship and its mission. Small airships may require a crew of one or two pilots occupying a properly equipped cockpit or flight deck in which are located all essential controls and instruments. Seats for passengers are usually removable to adapt the interior for other uses. A typical cockpit layout is shown in Figure 10.10. Controls for the pressure system are mounted above and to the pilot's side at head level. Ballonet damper controls are lever operated and mounted on the port eyebrow panel. Helium valve opening and closing handles are mounted overhead. Cables to air valves are connected to push rods at the pilot's left side. A bank of manometers indicating pressure in inches of water is suspended from the left eyebrow panel. These show ballonet and gas pressures. A dial gage displaying envelope (gas) pressure is mounted on the port flight instrument panel. Water ballast dump controls are located at the right side of the pilot's seat. Helium temperature and outside air temperature are monitored and displayed on the port indicator panel. A comparison of these readings allows the pilot to determine superheat values. An audible signal is sounded when helium pressure exceeds upper or lower limits. This is accompanied by a warning light on the instrument panel. An inclinometer is usually mounted at the pilot's side at head level. The Sentinel 1000 is equipped with both roll and pitch indicators.

A major improvement in flight control systems is incorporated in the Sentinel 1000 airship. This is an optically signalled flight control system called 'Fly-by-light.' It utilises fibre optics to transmit control commands directly to the surfaces. It also provides a stability augmentation system and autopilot functions. A side stick control is used instead of a control column. The valves, dampers, and scoops on this airship are pneumatically actuated and controlled by switches from the cockpit.

a. Port helium valve
b. Stbd helium valve
c. Circuit breaker panel (Fig. 10.3)
d. Manometer (Fig. 10.6)
e. Port indicator panel (Fig. 10.7)
f. Port flight instrument panel (Fig. 10.9)
g. Power levers (Port & Stbd engines)
h. Water ballast intake
i. Water ballast dump
j. Vector switch
k. Radio
l. Fuel controls port cross stbd feed
m. Ballonet damper controls
n. Centre eyebrow panel (Fig. 10.4)
o. Stbd eyebrow panel (Fig. 10.5)
p. Stbd indicator (Fig. 10.8)
q. Stbd flight instrument panel (Fig. 10.10)
r. Radio and radar

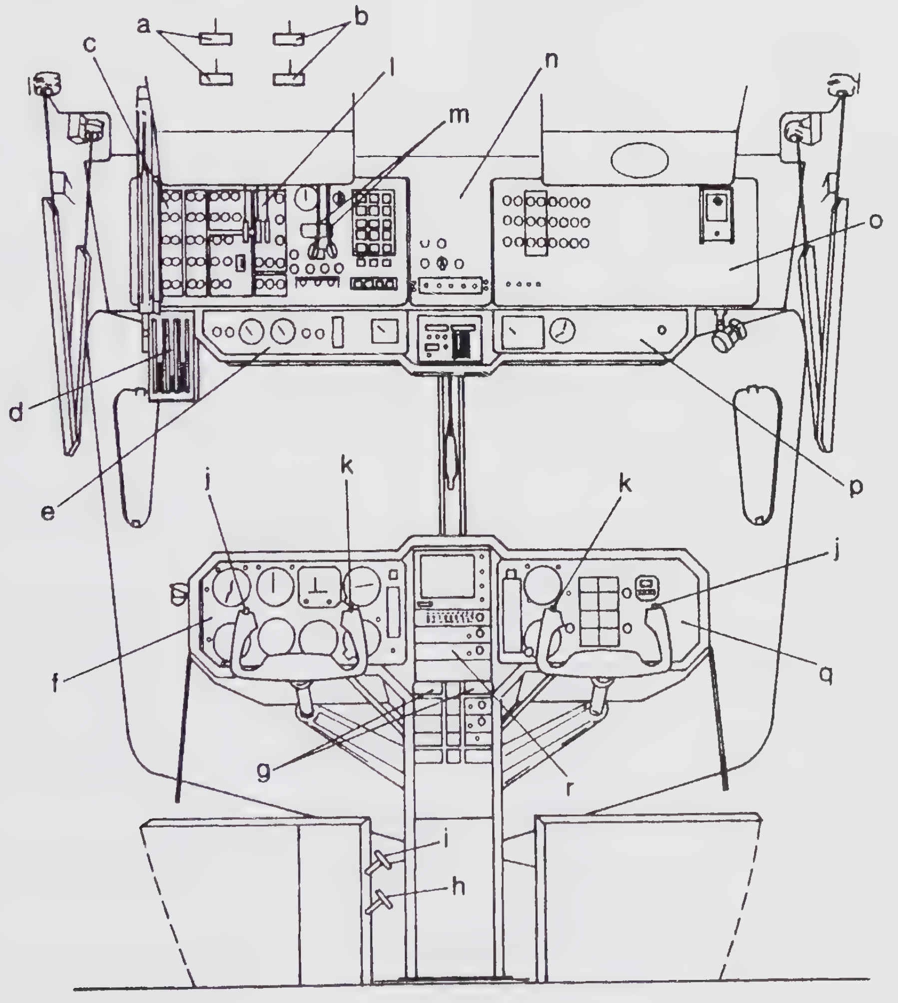


Figure 10.10. Typical cockpit layout.

Airships designed for long endurance and military missions must have facilities for the various specialists onboard as well as the flight crew (which may consist of several pilots). These may include pressurised cabins if high altitude operations are part of the mission. The design must include storage for potable water, a sanitation system, adequate ventilation, with suitably heated or cooled air, and hotel (sleeping and eating) facilities.

Electronic equipment, when in operation, sheds heat. This might be utilised for cabin heat or vented overboard.

ACCESS AND MAINTENANCE

Access to various parts of the airship is an important part of maintenance and safety. This is no easy task, even in small airships, because of the large dimensions involved compared with aeroplanes. Modern hydraulically powered platforms have made the job easier in the hangar. All external parts can be reached in a less hazardous manner than was the case in the past. The interior of the envelope is, for the most part, inaccessible, except for ballonet inspection and repair. These are entered through fabric sleeves at the bottom of the envelope. The rest of the envelope normally does not require interior access. Dome shaped windows installed at the bottom of the envelope - in the ceiling of the gondola - allow a visual inspection of the interior during flight or while moored. This feature is also useful during flight, for determining ballonet fullness.

The upper portion of the envelope's exterior is usually provided with manlines extending from the mooring cone to the empennage. These allow access by riggers when the airship is out of the hangar at the mast.

Vertical tunnels (trunks) have been used in rigids and in large non-rigids that allow personnel to reach the top of the envelope, even during flight. The U.S. Navy ZPG-2W and -3W airships included this provision to provide servicing and inspection of topside radar equipment. Figure 10.11 shows the location of a similar feature in the Sentinel 5000. These tunnels are constructed of gas-tight fabric and contain conveniently spaced rings that serve as handholds and steps for climbing. The system is supported from the top of the envelope and by cables.

Fill and purge valves can be installed in the forward and aft ends of the envelope to provide convenient connections for helium hoses during initial inflation and later for topping-off or purging to add helium.

Inflight servicing, particularly for large endurance airships, has led designers to opt for internal (to the car or hull) engine installations. This has been a feature on past U.S. Navy rigid airships and on the ZPG-2/2W series. It is also used on current Westinghouse airships and the projected Sentinel 5000. Although they are more accessible, they are usually more difficult to remove and replace compared with engines on outriggers.

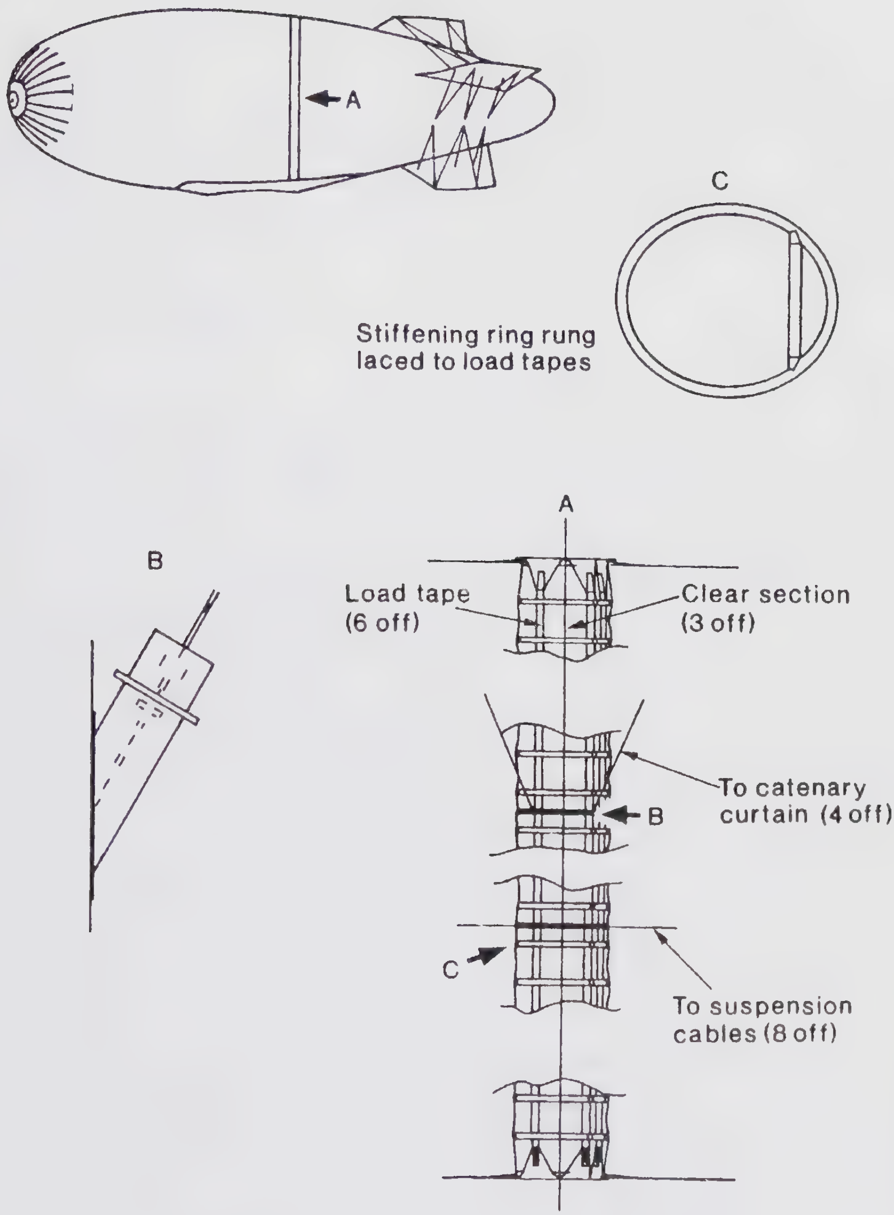


Figure 10.11. Upper envelope access trunk for the Sentinel 5 000.

Service experience with civil airships, particularly those used in advertising, has shown that outdoor operation can be a normal mode for the majority of the time in service. All routine servicing and maintenance is performed while the airship is moored. Removal to the hangar is scheduled for a two- or three-week period once or twice per year for major overhauls.

Rapid and easy servicing of major and minor components is an important part of airship operation and should be addressed in the design stage. Consideration must be given to sufficient clearance for removal and installation of components and making provision for special handling gear if required. Military specifications often include requirements for time and numbers of personnel required for maintenance and removal of parts.

EMERGENCY

There are emergency situations that may occur which require rapid deflation of the envelope. One of these would be an unpowered landing where no ground crews or mooring facilities exist. Deflation is accomplished through the use of a topside rip panel. This consists of a longitudinal opening, a long narrow slot, built into the envelope upper surface. The edges are reinforced with cable or heavy cord to contain the rip within the panel. The opening is covered with fabric with a ripping mechanism located at one end. This may consist of a strong tape, which is capable of severing the cover fabric when pulled through. In Westinghouse airships, an actual knife-edged cutter is used. Lines are connected to the cutter mechanism, one leading to the bottom of the envelope to a crew access point in the car. Another exits at the bow to allow a connection at the mooring mast. As a safeguard against accidental actuation, both lines are rigged through several tie points so that a considerable length of line must be pulled before any cutting action occurs. On small airships simple manual pulling only is required. The Sentinel 5000 design would incorporate a hand operated winch to assure sufficient pulling power. Figure 10.12 shows the location and some details of the installation on the Sentinel 1000. Some past airships have contained two rip panels. Current practice is to use one covering approximately 6 to 7 percent of the top centreline length of the envelope. The panel should be capable of venting about half of the gas in the first minute of operation.

Winter weather poses a particular problem for airships on the ground. Snow can accumulate in sufficient quantities to produce collapse of the landing gear or cause the airship to roll on its side. Removal is difficult owing to the heights involved. Methods used thus far include moving a long line along the top of the envelope or washing with a fire hose. Neither has been entirely satisfactory. A new system, proposed for the Sentinel 5000 would incorporate ducts along the top surface of the envelope through which anti-freeze solution could be pumped.

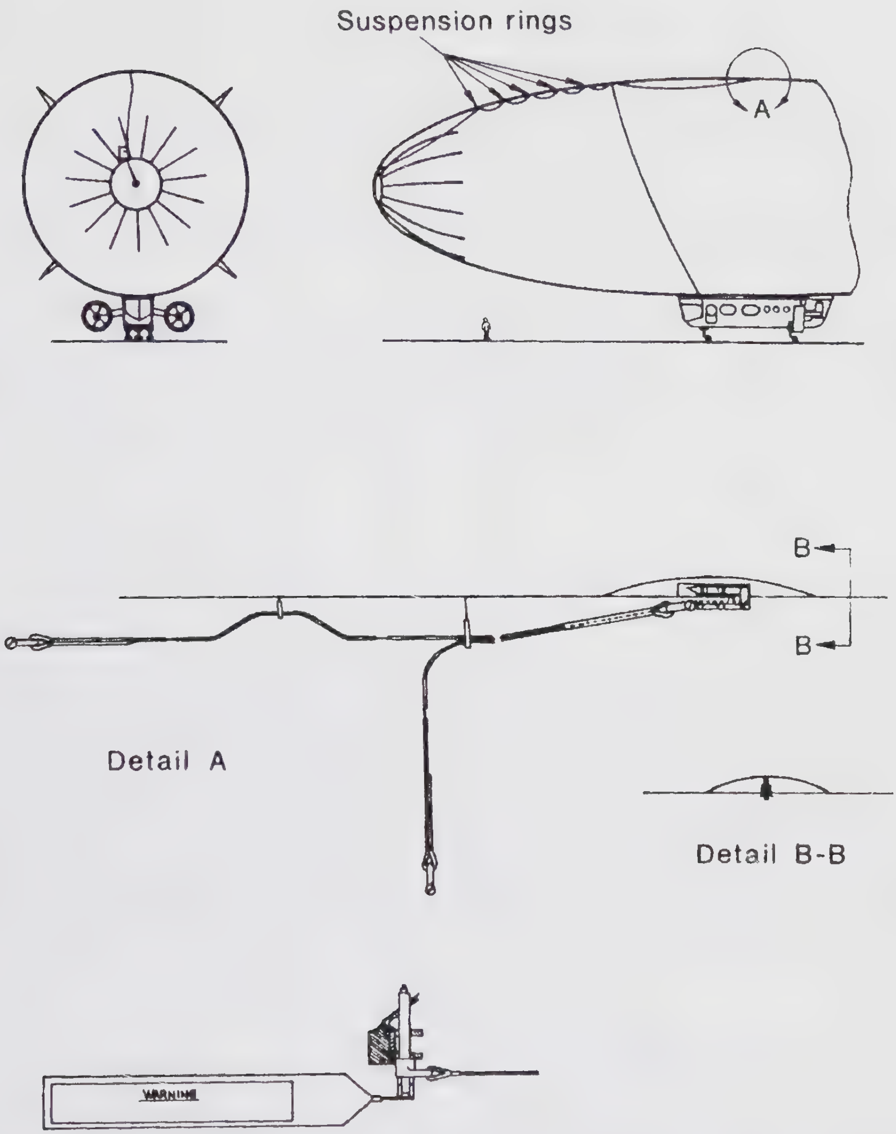


Figure 10.12. Envelope rip system and nose rip assembly (Sentinel 1000).

Crash landings must be provided for in design. Seats and support structure must be capable of withstanding the accelerated loads that may be produced. These are reflected in civil certification requirements in the U.K. and the U.S. as given in Table 10.2.

Table 10.2. *Ultimate inertia forces as specified in UK and US requirements*

Load Direction	Inertia Forces (g) Ultimate	
	U.K.	U.S.
Up	1.5	0
Down	4.5	3.0
Forward	4.0	2.5
Rearward	4.0	1.0
Sideways	0-4.0	1.0

Crash stations are specified for military airships that require large crews. These are placed at locations not likely to fail on impact and are near exits. Civil airships use removable windows as emergency exits in addition to the entrance doors.

When an airship vents gas in addition to air, it is possible that the volume discharged may exceed the capacity of the ballonets to compensate, a condition known as exceeding ballonet ceiling. This could cause the envelope to lose form as lower altitudes are reached. This can be prevented by blowing air directly into the helium space, and a special sleeve or rip panel is provided in the air supply system to allow this to happen.

AUXILIARY THRUST

Several methods have been used or proposed to increase airship control, particularly during low speed flight. Some notable examples include the French Oehmichen Helicostat, which incorporated multidirectional thrusting propellers all driven by a single engine, and the Italian Forlanini Omnia Dir, which contained bow and stern high pressure air jets. Both airships were built in the early 1930s. More recently, the hybrid Piasecki Helistat combined four helicopters with a surplus U.S. Navy ZPG-2 envelope. All of these were experimental designs. By far the most successful arrangement has been one where the main propulsive units are vectored vertically to achieve positive or negative thrust up or down. This concept has been used on several past airships, including some of the early British rigids and the U.S. Navy rigids ZRS-4 and 5. Currently, it is used on all Westinghouse airships and on the Goodyear GZ-22.

Thrust vectoring can be achieved either by swivelling the propulsive ducts and propellers as is done in the Westinghouse designs or by rotating the entire engine and propeller units as in the Goodyear design, which is equipped with Allison turboprop engines mounted externally. The Westinghouse airships have engines mounted in the car and drive the propellers through long shafts. The gear boxes used are an adaptation of standard helicopter tail rotor units. The propulsion ducts are vectored by electrically driven shafts. Cross coupling of the shafts ensures simultaneous rotation of the ducts and also allows one vector motor to drive both ducts in the case of partial motor failure. Manual operation is also possible in the event of complete power failure.

While these vectoring systems achieve a degree of vertical thrust, it continues to be a desirable goal to gain improved multidirectional control at low speeds by thrusting at the bow or the stern. Efficient and low drag mounting of thrust units is a problem, but it can be expected that experiments will continue along these lines.

REPLENISHING

Military airships operating in conjunction with naval surface vessels can be equipped for inflight replenishing. This would include transfer of fuel, weapons, life support provisions (food, etc.) and exchange of personnel. The surface vessel carries the items required and transfer is accomplished using a winch on board the airship. This procedure was used in the 1950s by the U.S. Navy. Current military versions of the Sentinel 5000 design would include similar operations.

Refuelling is accomplished by lowering a cable to the deck of the surface vessel from the airship, flying at an altitude of about 300 feet. Attachment is made to the end of the refuelling hose nozzle. The hose is hoisted to the airship and seated in the fuel system receptor, following which fuel is pumped from the ship. If the airship exceeds certain defined limits of movement or position so as to cause the hose tension to increase, fuel flow is automatically interrupted and the hose rapidly evacuated. The airship releases water ballast as the fuel is delivered.

Another method of fuel supply involves the use of fuel bladders. These are large pliant pillow-shaped containers stored on the surface vessel, filled with fuel, and lifted directly by the airship. They can also be floated in the sea prior to pick up. This method has the advantage of supplying a large quantity of fuel quickly; pumping is not required, and the bladder can be dropped instantly should this be necessary. However, there are more hazards involved in this system and greater manpower and preparation are required on both the airship and the surface vessel. It has been demonstrated.

Transfer of personnel is performed by the use of a small car or basket stored on the ship. The lifting of up to four persons at a time has been demonstrated.

The hoisting station was positioned at the aft end of the car on U.S. Navy airships, as was the winch and fuel system connections. In the current Sentinel design the replenishing station is located in the middle of the car.

Winches should be equipped with approximately 1000 feet of cable and have sufficient capacity to lift any of the items required. A 3000 lb. capacity covers most of the requirements. Hydraulically driven winch motors have been used and are planned in current designs.

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11

Ground Handling and Mooring

D. Howe

INTRODUCTION

The difficulties encountered in the design, construction and operation of a vehicle are usually directly related to its fundamental concept. This is certainly true of airships, as may be seen by a review of experience gained during the first half of the twentieth century. Essentially three main problems were encountered, all of which have a direct bearing on ground handling and mooring.

Lifting Gas Management

Hydrogen filled airships were prone to catastrophic fire, especially when adjacent to the ground. This was a direct consequence of both the use of an inflammable gas and the methods used to control the buoyancy of the craft. The latter usually paid no attention to the probable fire hazard, being determined primarily by simplicity of design and operation. Landing the airship could be a particularly dangerous time due to the frequent use of haphazard hydrogen venting to reduce aerostatic lift on the descent, coupled with the possibility of static electricity discharge as contact was made with the ground. The well known image of the 'Hindenburg' catastrophe at Lakehurst in 1937 clearly shows that a mooring line has just been made fast. Interestingly the most successful rigid airship, 'Graf Zeppelin 1', minimised the need for venting hydrogen by using a fuel having the same density as air. The exclusive use of helium as the lifting gas in current airship concepts totally overcomes this difficulty, and - in any case - the cost precludes the use of direct gas venting.

Structural Design

It was found to be extremely difficult to produce a satisfactory lightweight structure. This was especially true of the larger, rigid, airships where often relatively minor damage resulted in catastrophic failure. Non-rigid craft which use internal pressure to stabilise the envelope are less susceptible to this problem, but are inevitably limited in size by the properties of available materials. This particular problem was a consequence of a number of things. These included a lack of knowledge of structural loads, especially those caused by atmospheric turbulence; limitations in the strength of available materials; and very limited analytical aids. Whilst material properties are now much improved and adequate computational facilities are available, the problems of dealing with points of concentrated load input still remain, as do the vagaries of weather conditions. Both of these considerations are of special relevance to the requirements of ground handling and mooring. The consequence of a structural failure whilst an airship is moored was illustrated by an incident which involved the rigid airship R-33 although in this case the craft was successfully recovered.

Ground Handling

Ground handling of airships has always presented problems; it is almost certainly true to say that a fully satisfactory solution has never been achieved for larger craft. In many instances recourse was made to the use of large numbers of men, with the attendant difficulty of precise control as illustrated by the photograph of the R31 (Figure 11.1). However, even the use of more automated techniques was not without problems.

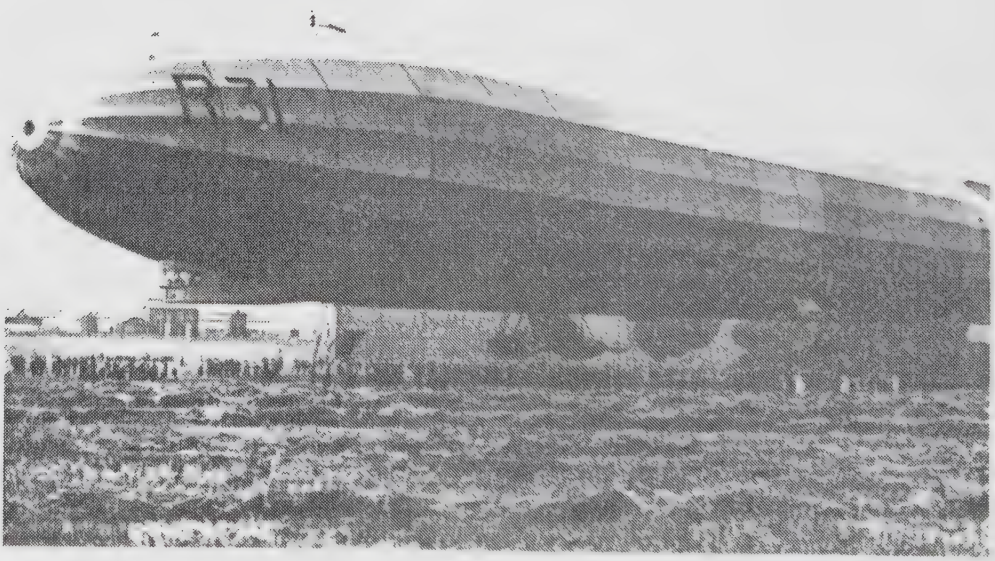


Figure 11.1. Manual handling of R31.
(Credit: Imperial War Museum)

A significant contribution to the difficulties was the state of powerplant design in the large airship era. Because of the relatively low power/weight ratios of suitable engines it was not possible to provide really useful levels of vectored thrust to assist in the general ground handling phases, although the potential for this was realised and some attempts made to apply it. There can be little doubt that the whole area of ground handling remains as the outstanding difficulty in airship design and operation. Whilst adequate techniques have been devised for use with smaller, non-rigid, craft, these are unlikely to be satisfactory for application to large, heavy lift airships should these become a reality. It is therefore in order to consider the issues involved in more detail.

SURVEY OF THE GROUND HANDLING PROBLEM

The dependence of the airship on aerostatic lift confers upon it the possibility of vertical take off and landing; it is, however, this dependence that gives rise to ground handling problems. In order to have a useful lifting capacity it is inevitable that the airship possesses a large gas volume, which implies a large surface area. Hence the airship is very sensitive to atmospherically derived forces, whether they arise from discrete gusting or more generally random turbulence. Further by its very nature the true airship must be anchored to the ground by some means when it is not in flight, unlike a heavier than air machine where, for the most part, this is only a secondary consideration.

A very important consideration is the means used to control the airship. Whilst the craft is underway the use of aerodynamic forces for control is relatively straightforward and all designs take advantage of this. Some airships also make use of limited thrust vectoring. However, both the magnitude and response of aerodynamically derived control forces decrease as forward speed is reduced towards zero for ground operations. Thus these devices are of negligible use in providing control to counteract the effects of atmospheric turbulence. In fact the dependence upon aerodynamic control is in direct contravention of the primary advantage of aerostatic lift in conferring vertical take off and landing capability. Some amelioration is possible by resorting to short take off and landing, but any significant compromise in this respect removes one of the major operational advantages of the airship.

The appreciation of the fundamental difficulty of ground handling led Professor Morse, of Boston University (*New Scientist*; 7 April, 1966), to propose a nuclear powered airship that would effectively remain in the air throughout its life. He suggested that heavier than air machines would be used to transfer people and supplies to and from the ground, a technique pioneered both in the United Kingdom and the United States, primarily for military purposes.

GROUND HANDLING AND MOORING REQUIREMENTS

A more specific statement of the requirements of the various aspects of ground handling is appropriate.

Hangarage

Clearly, it is necessary to provide a shed for the erection of an airship and for undertaking major refurbishment. It is also usual for an airship to be protected from the weather whilst it is being stood down from operations for a lengthy period. Unfortunately, as the removal and re-entry procedures are some of the most hazardous operations, there is good reason for keeping the airship outside if weather conditions permit. The large size of the craft implies a very large building for hangarage purposes. Figure 11.2 shows one of the two sheds at Cardington. It is really only possible to contemplate this at one base and hence it could prove to be a limitation on operational capability.

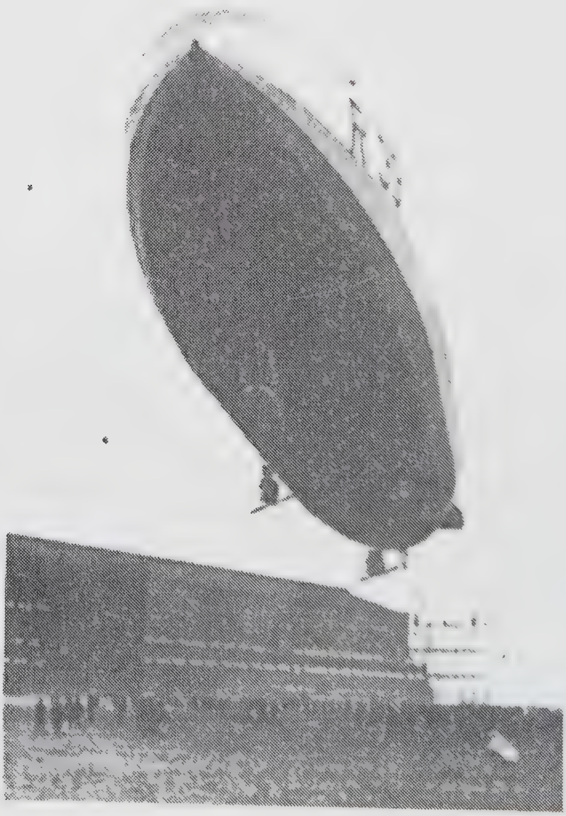


Figure 11.2. Airship R33 departing Cardington with shed in background. (Credit: Imperial War Museum)

There may, however, be the possibility of a compromise. For example whilst the airship 'Norge' was being operated at Spitzbergen Island in 1926, protection from the adverse weather was provided by two parallel walls between which the craft could be positioned. Because of the hazards associated with moving an airship into and out of a hangar it is desirable to use a building of generous width, thereby reducing the risk of the craft being blown into the wall should a sudden gust arise. As far as possible the shed should be aligned in the direction of the strongest winds, to minimise cross wind effects.

Ground Movements

As stated in the previous paragraph the movement of the craft from its shed is a hazardous process. The logic of restraining the airship so that any gusting does not result in significant deviations from its intended path is likely to introduce as many difficulties as it may resolve. Large loads can arise at the restraint attachments. There is a consequent likelihood of damage being caused unless a large structural weight penalty is accepted. Even when the airship is clear of the shed, serious difficulties remain. Some degree of restraint is still required as well as motive force to move the craft to its intended location. Subsequent operation is simplified if the airship can be moved with the device which is to be used to moor it.

Mooring - Loading and Unloading

Apart from such radical concepts as that proposed by Morse it is necessary to moor the airship when it is not in operation. Mooring may be required for the purposes of loading and replenishing the craft or, frequently, simply for standing down between operations. The essential requirement for the mooring system is that it must be capable of making the craft secure under all anticipated weather conditions, without the imposition of unacceptably high loads on the structure. This proves to be a central consideration both in terms of the technique adopted for mooring and in the determination of structural strength. Whilst the mooring concept may influence the way by which the airship is manoeuvred from the hangar to the mooring location, it is much more likely to influence, and be influenced by, the procedure employed for recovery at landing.

Lift-Off

On the whole this is one of the less demanding aspects of airship ground operations. Although it is necessary to provide adequate control in the critical phase until normal operating height and speed have been reached, other considerations are likely to ensure that this is the case. In principle all that is needed is for the craft to be released from its moorings, but in practice it is somewhat more complex than this. In particular control of the operation must ensure that there is no danger of contact with ground equipment. This is especially a consideration when, as is often the case, a short take off technique is used to develop some aerodynamic lift for upwards acceleration and control, rather than having excessive aerostatic lift.

The Recovery Phase - Landing

Together with the removal of the craft from its hangar, recovery on return to the ground provides the most demanding of the ground handling problems. In this the airship is no different from the heavier than air machine where landing is demonstratively the most hazardous part of a flight. The reason lies in the need to reduce to zero both the horizontal and vertical energy associated with the approach to landing. On the face of it this should be much easier to achieve with the airship since, fundamentally, it possesses a lift equivalent to its weight which is independent of forward speed. The problem is simply the susceptibility of the craft to wind variations and probable poor response to control demands, characteristics shared by conventional aeroplanes having a low wing loading. The accurate positioning of the airship to enable it to be attached to its mooring equipment is difficult and can be a tedious procedure. Even more difficult is the related operation of accurately positioning the craft in a stationary mode for the purpose of lifting or placing a heavy load. Some easing of the hazards may be achieved by accepting a short, rolling landing but it is still necessary to capture the craft and bring it to a standstill. As was stated previously there is a close relationship between the recovery and mooring techniques.

Summary

From this survey of the ground handling requirements it can be concluded that once the airship is clear of its shed, the most crucial consideration is the provision of adequate low speed control. The philosophy adopted for recovery and mooring dictates the design concept and other aspects are then most likely to be adequately covered. Providing satisfactory mooring can be achieved under all probable weather conditions, the use of a hanger is best avoided whenever this is possible.

HISTORICAL REVIEW OF GROUND HANDLING TECHNIQUES

The Nineteenth Century

The earliest attempts to develop from balloons to craft capable of some degree of controlled flight were made towards the end of the nineteenth century. Ground handling considerations were of little concern at this stage of airship development and relied somewhat haphazardly on the ability, or otherwise, of manpower to release and, rarely, safely recover the craft.

The Pioneering Era

Serious airship development can be dated as beginning in 1900 when Count von Zeppelin's LZ-1 craft was completed. It is probably true to say that this was the first design where all aspects of airship operation had been carefully considered and the matter of ground handling given serious thought. Zeppelin realised that his large, light craft would be susceptible to wind variations and planned his 'ground' operations on the basis that they would be undertaken from the waters of Lake Constance. Apart from giving a clear, uncluttered surface area it also facilitated the ground manoeuvring of the craft. LZ-1 was constructed in a special floating hangar and positioned on a floating pontoon. The airship had two gondolas connected by a girder. This was used on the one hand to moor the craft and on the other to distribute the loads into the hull structure. Operation on water enabled the hangar to be aligned into the direction of the wind in order to minimise the difficulties of removing the airship, which was done by towing out the pontoon. Further, once clear of the hangar the effect of wind variations was reduced both by the freedom of the craft itself on the mooring ropes and by movement of the pontoon in the water. As can be seen reliance was placed on manpower both to release the craft at lift off and also to recover it at the end of the flight. Launch was accomplished by simultaneous release of the mooring ropes with, if necessary, release of water ballast to ensure that the craft climbed away. Recovery was a more difficult procedure involving vertical control by venting of lifting gas again supplemented by ballast release if needed. Considerable reliance was placed on the skill of the captain and the courage of the ground crew in catching the mooring lines. Adjustment of engine power gave only limited control in the horizontal plane. Reports indicate that the first flight of LZ-1 was somewhat problematical and ended in an uncontrolled landfall away from base. The flight started badly with the nose ropes being released prematurely and longitudinal balance control was unreliable.

Six years elapsed before LZ-2 was ready and its fate illustrated graphically the problems of ground handling. After some initial damage during removal from its shed it was destroyed at its moorings when a squall blew up overnight. Whilst LZ-3 was successful LZ-4 was destroyed by fire as a direct consequence of its breaking away from a temporary mooring. Generally the early Zeppelin airships retained the same basic concepts and were moored primarily from their gondolas.

The British Naval Airship No. 1 of 1911 used some similar principles for ground handling as those used on LZ-1. It was built in a floating shed by Vickers at Barrow, and towed out for operations. There was, however, a significant difference in that it was moored by its nose to a mast and was supported on the water by floats on its two gondolas. The mast was mounted on a float secured to a concrete base and was arranged to rotate so that the moored airship always tended to align to the wind direction. The mooring concept itself proved to be successful in that the craft withstood windspeeds of above 40 mph. Unfortunately, 'Mayfly' - as it became known - was somewhat heavy and initial attempts to fly were unsuccessful. This may, in part, have been due to the fact that it was the first airship to employ a duralumin rather than wood construction. The airship was returned to its hanger for modification which included structural modification to reduce weight. Sadly disaster struck as the craft was then being removed from the shed. A gust of wind caused the hull to twist and finally broke its back. Although 'Mayfly' did not fly it did result in a significant development in mooring technique.

Other airships that operated from land had to be taken out of their sheds by 'walking out'. This was a process even more hazardous than that associated with floating hangars and literally involved the coordinated efforts of many men to remove the craft from the constrained space of the hanger. The operation was particularly sensitive to sudden wind gusting just as the craft finally left its protection.

It was not long before it was realised that one of the main problems associated with ground handling was the almost total absence of directional control, as the conventional aerodynamic controls used for cruising flight were ineffective at low speed. The only alternative source of control forces was the powerplants and the idea of using this in the form of vectoring propellers was introduced in the British Army airship 'Gamma'. 'Gamma' was constructed at the Army Aircraft Factory at Farnborough and was a comparatively small, non-rigid, craft. For experimental purposes the single engine originally used was replaced by two smaller units each of which drove a propeller capable of being swivelled through 360^{o} in a vertical plane. Thus the engine power could be used to augment or reduce lift as well as providing a reverse thrust capability. The experiment was successful and 'Gamma' could lift off and land without the need for any provision except a small handling party.

Count von Zeppelin had, meanwhile in 1909, formed the world's first airline, DELAG, and provided it with several airships. Of this initial batch at least three were lost but without injury to crew or passengers. LZ-8, for example was lost whilst landing and docking. In 1911 a new craft, LZ-10 'Schwaben' was introduced. The design incorporated the lessons learnt from the earlier accidents. Amongst the innovations was the use of 'handling' rails. The handling lines were attached to bogies which ran along the rails thereby enabling the craft to be controlled in higher wind conditions with few men. Although LZ-10 was destroyed as a consequence of a fire in its hangar in 1912, it's three sister ships continued to operate successfully until the outbreak of war in 1914.

Development of the Mooring Mast

Many of the early airships were moored by two or more tethers, much in the same way as a ship is docked. When adverse weather conditions were forecast the craft were moved into their sheds, the hazards of this operation being accepted as the lesser of the two operational problems. It was soon realised that multi-point mooring could cause large structural loads under gusting conditions, and as a consequence research into mooring systems was undertaken. A major development in this was the rotating mooring mast used for the British 'Mayfly' airship, referred to above . The technique used in this case was a hybrid arrangement with the airship supported in the vertical sense by its two floating gondolas, thereby also allowing surface access to the craft. Such a system was only directly applicable to water borne operations and it was not long before the concept of single point mooring was adopted. In this technique the airship is constrained only at its nose and is allowed to yaw and pitch about this point, thereby minimising steady wind loading. Sudden gusting can still impose large loads during the transient phase before the craft can fully respond. A disadvantage of single point mooring is the large ground area required to give the airship a full 360° clearance in the rotational, that is yawing, sense.

The advent of single point mooring introduced the question of the mooring height. In the first instance there was a general trend for the airship to be moored so that the gondolas were close to the ground facilitating access to them as well as minimising the required mast height. Whilst such a system clearly has some major advantages, it does mean that if the airship is subjected to significant pitching moments, there is a real possibility of serious damage arising from contact with the ground. There are two obvious ways of overcoming this:

a) By adopting a second tether, located near to the stern of the airship. If the tether is attached to a trolley or bogie it can be arranged to move more or less freely in the lateral sense. This restrains the craft in pitch whilst allowing yawing motion against side winds which are the cause of the most serious loads.

b) By using a mooring mast of sufficient height to ensure that there is no danger of the craft striking the ground, even in the most severe conditions. The disadvantages of this are the need for a substantial mast structure and the much more difficult access for loading and unloading. Nevertheless the majority of the later, large British rigid airships were operated from high level masts. The availability of suitable masts tended to restrict the flexibility of operation.

Some idea of how mooring masts developed in the United Kingdom can be seen by reference to Figures 11.3 to 11.5.

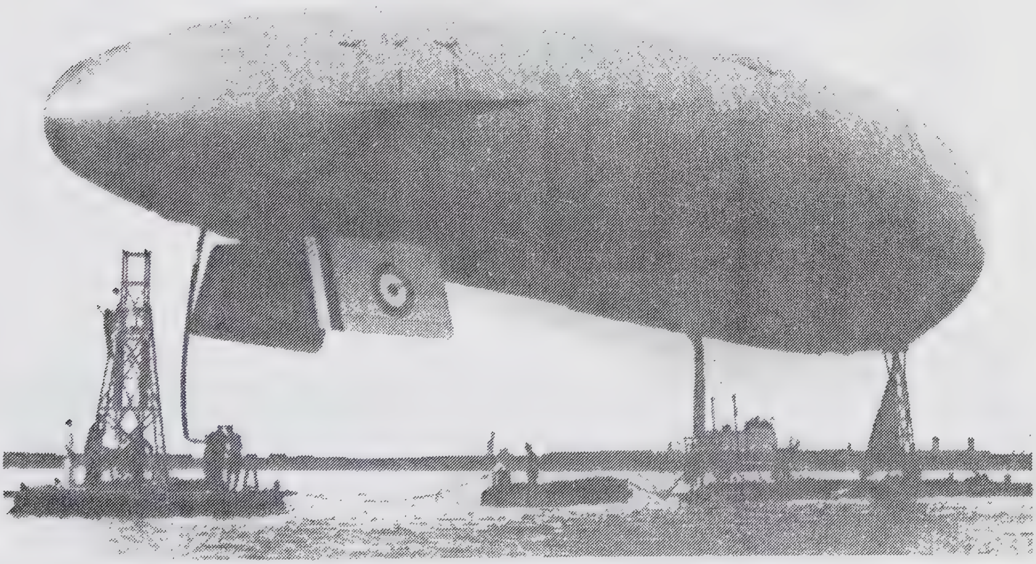


Figure 11.3. Water based mooring experiment at Barrow-in-Furness. Experiments result in preference for land based mooring. (Credit: Imperial War Museum)

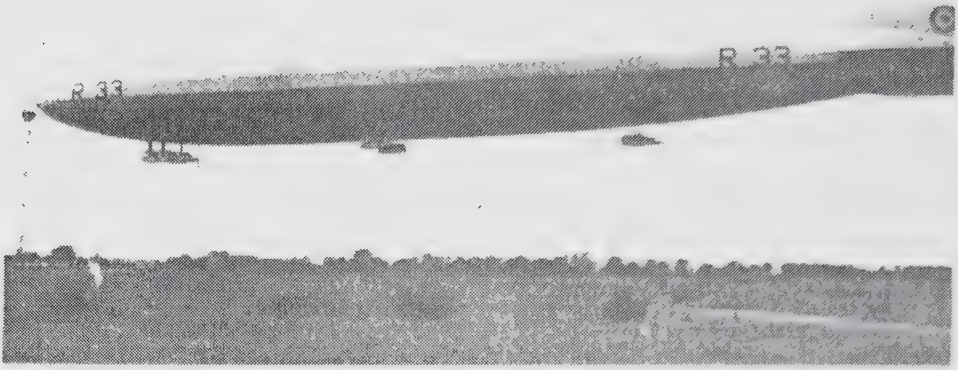


Figure 11.4. Airship R33 at Pulham mast.
(Credit: Imperial War Museum)

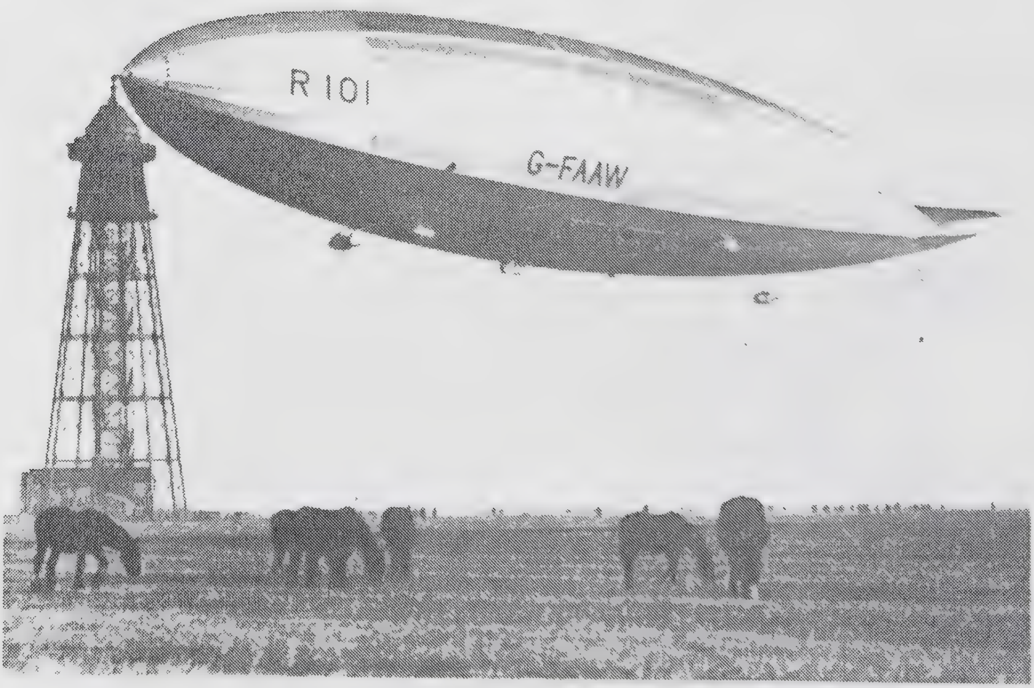


Figure 11.5. Airship R101 at mooring mast.
(Credit: Imperial War Museum)

The first of these shows the early water based concept and the second the R-33 moored at its Pulham base. The Pulham mast was slender but proved to be very satisfactory. During a 96 day period in the late winter to early summer of 1921, R-33 was moored continuously at the mast. The airship successfully rode out winds that gusted to 55 mph. It should be pointed out that during such operations there was always a crew on board whose task it was to 'fly' the airship if weather conditions so demanded. Later, in April 1925, R-33 was subjected to several very severe gusts whilst at the Pulham mast and these caused a failure of the local structure in its nose and consequent breaking away from the mast. However, after over a day of struggle against the very severe weather conditions the crew were able to recover the airship back to Pulham where it was repaired and strengthened. Figure 11.5 shows the ultimate British development of the high level mooring mast with R-101 about to moor at Cardington. The spiral staircase and central elevator located within the mast can be seen. These provided access to the top of the mast and the airship. The airship was flown onto the mast which often proved to be a long and tedious process.

Masts were also developed in the United States. For example, the last United States rigid airship, the 'Macon', used a large and substantial mast. The mooring line was attached prior to docking to enable it to be winched onto the mast. Such a technique is much less fraught with danger than that used by R-101.

Clearly such massive mast structures were only suitable for fixed based operations. Lighter, and usually, lower masts had to be employed in other circumstances. In general operation from water is less likely to cause severe up and down gusts and so a lower mast may be satisfactory. The 'Los-Angeles' moored to the ship 'Patoka' immediately after having made a successful landing on the aircraft carrier USS 'Saratoga' without the benefit of a mooring mast. Comparatively light, mobile mooring masts have proved reasonably satisfactory for smaller non-rigid craft.

Recovery on to low level masts often involve the craft making a slow landing, it being initially constrained by manpower. It is then either 'walked' to the mast or a mobile mast attached to it. Most recent airships have a wheeled landing gear to facilitate this procedure. The high level mast does provide the opportunity to recover the craft without external assistance. However, as has been found with ships, a limited degree of human interaction greatly facilitates the process.

Low Speed Control

In parallel with the development of mooring techniques there were attempts to improve the low speed control characteristics of airships, primarily by utilising powerplant thrust.

UK airship No.9 was a direct derivative of the ill-fated No.1. Apart from having an improved design of structure it adopted the vectoring propeller principle first demonstrated on 'Gamma'. As originally built it was fitted with four engines of 180 HP each driving a propeller capable of being swivelled up or down and ahead to astern. Unfortunately it was somewhat overweight and one of the steps taken to resolve this was the removal of the swivelling gear. In this it set a pattern for future British airships. Whilst designers and operators clearly realised the potential advantages of vectored thrust, it would seem that the limited forces produced by the relatively low powered engines available did not operationally justify the associated weight and complexity. Airships Nos. 23 and R-26 were developments of No.9 and were also fitted with four engines, in this case of 250 HP each. The engine in the forward gondola was used to drive a pair of swivelling propellers, as shown in Figure 11.6. The central and rear engines drove standard propellers. R-25, another airship in the same series but built by Armstrong-Whitworth rather than Vickers, started life with single swivelling propellers on both the front and rear two of the four engines, but the swivelling gear was removed later. A similar policy was adopted on the R-29 development of R-25.

The next generation of British airships, R-31, R-33, R-34, R-38 and R-80 did not incorporate vectoring propellers. They all, however, employed reversing gear on some of their engines, thereby conferring the ability to give precise fore and aft control during recovery. As an example R-33, arguably the most successful British rigid airship, was fitted with four engines each of 275 HP. The engine arrangement was unusual. There was a single engine behind the control car at the front, a pair amidships and two rear engines geared together to drive a 19ft diameter propeller. The central pair each drove a 16ft diameter reversing propeller.

Figure 11.6. Control car of Airship no. P6 showing swivelling propellers. (Credit: Imperial War Museum)

With possibly only one exception subsequent rigid airships were fitted with some reversing propellers rather than vectoring ones. For example R-100 was equipped with 6 engines of 670 HP each, arranged in three pairs consisting of a tractor and pusher propeller. The pushers were reversible. R-101 was an exception. Although this airship has a bad reputation because of its catastrophic demise it was a craft of great potential and incorporated a number of novel features. Unfortunately, as had been discovered on No.9, these resulted in high weight and no time was given to enable the problem to be resolved properly. Amongst the features were diesel engines driving vectoring propellers.

FORCES ON AN AIRSHIP WHILST MOORED

The forces and moments experienced by an airship whilst it is moored or being ground handled arise from several causes:

a) Inertial effects as a consequence of its own mass undergoing handling accelerations.

b) Steady wind effects.

c) Atmospheric turbulence.

Of these the first cause is directly under the control of handling system whilst, at least to some extent, steady wind conditions are predictable and can be allowed for. General turbulence, however, is random and includes discrete gusting, which is essentially unpredictable both in frequency and magnitude. It is this which gives rise to the main difficulties associated with ground handling generally. To attempt to design an airship structure and mooring system to meet every conceivable possibility would not be practicable either technically or economically. Hence it is necessary to establish a design case based on the most severe conditions expected at a given probability of recurrence. This is by no means a straightforward procedure as nature is likely to produce the unexpected.

During ground handling the forward speed of the airship is low in comparison with likely wind speed, whilst it is zero when it is moored. The aerodynamic effects resulting from winds are partly reacted by the constraints imposed by mooring or handling and partly by inertial effects as the craft responds to the applied forces. In cruising flight the aerodynamic disturbing effects are reacted to by natural stability, control and inertial effects, so the conditions are quite dissimilar.

The steady force conditions in the vertical plane appropriate to a moored airship are shown in Figure 11.7a. The case illustrated is where the craft is moored at two points, thereby avoiding the added complexity when multipoint mooring is employed.

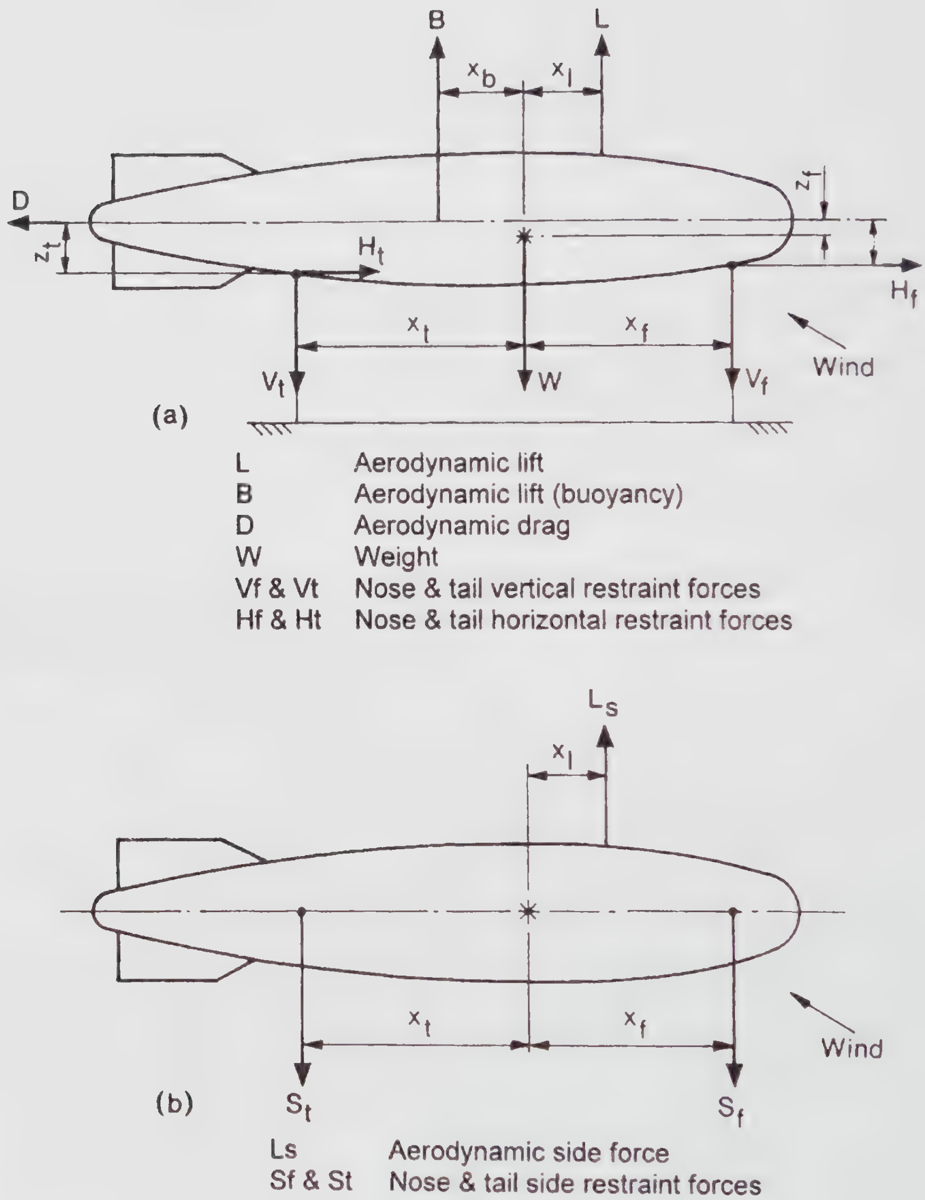


Figure 11.7. Forces on a moored airship.

The use of two mooring points may be assumed to imply that there is no translational or angular motion of the craft. Aerodynamic lift, which may arise from wind effects, is shown as acting at the centre of pressure. Resolution of the forces in the horizontal direction gives:

$$H_f + H_t - D = 0 \tag{11.1}$$

Resolution of the vertical forces:

$$W + V_f + V_t - L - B = 0 \tag{11.2}$$

Moment equilibrium about the centre of gravity:

$$Lx_l + V_t x_t - Bx_b - V_f x_f + H_f z_f + H_t z_t = 0 \tag{11.3}$$

Solution of these equations presents some difficulty since the reactions of aerodynamic drag (Equation 11.1) depends on the structural stiffness of both the airship and the mooring device. This, however, may be overcome if it is assumed, for example, that the tail mooring is so designed that it reacts only to vertical load, that is:

$$H_t = 0 \qquad\qquad D = H_f$$

Equation 11.2 may be written as:

$$V_t = L + B - W - V_f \tag{11.4}$$

and when substitution is made for H_f and V_t into Equation 11.3:

$$V_f = \left[L(x_l - x_t) - B(x_b + x_t) + Wx_t + Dz_f\right] / (x_f + x_t) \tag{11.5}$$

which can be evaluated for given values of the applied forces and Equation 11.4 then used to obtain V_t.

In general there will also be forces acting sideways owing to cross winds on the airship and these are likely to be more severe than those in the vertical plane. A simple situation is shown in Figure 11.7b.

Lateral force equilibrium gives:

$$S_f + S_t - L_s = 0 \tag{11.6}$$

and moment equilibrium:

$$S_f x_f - S_t x_t - L_s x_l = 0 \tag{11.7}$$

Substitution for S_t from Equation 11.6 into Equation 11.7 gives:

$$S_f = L_s(x_l - x_t)/(x_f + x_t) \qquad (11.8)$$

The fact that the aerodynamic side force will, in general, act above the mooring points will result in a rolling tendency. The reaction of this is a complex interaction of the aerodynamic forces in both the side and plan elevations, including the forces on the fins. The tendency may be avoided by raising the nose mooring point to the same height as the side lift and designing the rear point so that it cannot react to side load.

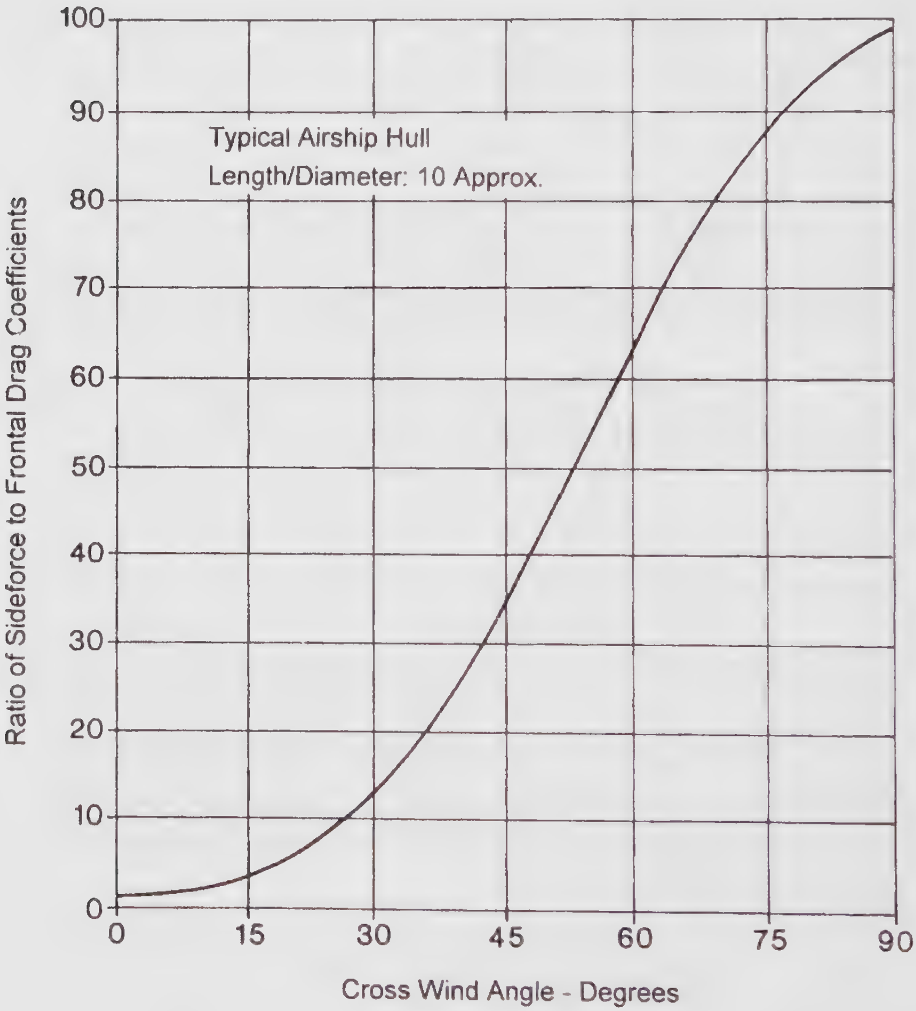


Figure 11.8. Variation of side-force coefficient on an airship hull with cross wind angle.

The situation relevant to single point mooring can be deduced from the above equation. In the side elevation from Equation 11.1:

$$H_f = D \tag{11.9}$$

and Equation 11.2:

$$V_f = L + B - W \tag{11.10}$$

and to obtain moment equilibrium also, from Equation 11.5:

$$V_f = \left[Lx_l - Bx_b + Dz_f\right] / x_f \tag{11.11}$$

Equating Equations 11.10 and 11.11 gives:

$$L(x_l - x_f) - B(x_b + x_f) + Wx_f + Dz_f = 0 \tag{11.12}$$

and for the case when there are no applied aerodynamic forces:

$$x_f = Bx_b / (W - B) \tag{11.13}$$

This implies that for the case when the buoyancy is equal to the weight and the centre of buoyancy and centre of gravity are coincident, the position of the mooring point does not affect the moment equilibrium in the absence of wind induced forces. Using this condition Equation 11.12 reduces to:

$$x_f = \left(x_l - \frac{L}{D} z_f\right) \tag{11.14}$$

where L/D is a defined characteristic of the airship.

Alternatively, if a nose mooring point is used, so that z_f is effectively zero, Equation 11.12 becomes:

$$\frac{L}{W} = \left[\frac{B}{W}(x_b + x_f) - x_f\right] / (x_l - x_f) \tag{11.15}$$

Since x_f is defined in this case, as are the other items on the right hand side of the equation, it is necessary to 'fly' the airship to ensure that L/W has the value to give equilibrium. If, however, there is no wind, the lift can only be zero which leads to:

$$\frac{B}{W} = \frac{x_f}{(x_b + x_f)} \tag{11.16}$$

as a condition to ensure moment equilibrium at all conditions. Substituted back into Equation 11.15 this implies that such an airship must be in a zero lift condition at all times.

The major advantage of single point mooring at, or near to, the nose is that it enables the airship to weathercock into the wind direction, thus eliminating the side forces owing to steady conditions. Gusting side wind components induce side loads during the transition phase during which the airship returns to its stable directional condition. The importance of the weathercocking facility conferred by single point mooring can be seen by reference to Figure 11.8. This shows the variation of force coefficient as a function of crosswind angle for an airship configuration having a length to diameter ratio in the order of ten. The coefficient is based on the frontal area for consistency. It can be seen that in a 90° crosswind the force is two orders of magnitude greater than that at zero angle, this latter being effectively the conventional drag force. An idea of the moment associated with this force can be gained by noting that the centre of pressure moves back from the nose to reach the centre of buoyancy at a cross wind angle of about 45° and then remains more or less constant in position.

THE EFFECT OF SIZE ON GROUND HANDLING

A simple application of the square-cube law suffices to demonstrate the impact of size of an airship on forces and moments related to ground handling.

The lifting capacity is a function of volume, thus to the first order:

a) $M(\text{Mass}) \;\alpha\; \text{Volume} \;\alpha\; l^3$

where l is a typical dimension, say length.

b) Aerodynamic force is a function of area:

$F_A \;\alpha\; l^2 \;\alpha\; M^{2/3}$

c) Moments due to aerodynamic forces are:

$M_A \;\alpha\; F_A.l \;\alpha\; l^3 \;\alpha\; M$

d) The response of the airship to applied moments is a function of the effective moment of inertia, which includes the virtual inertia of displaced air. This is:

$I \;\alpha\; Ml^2 \;\alpha\; M^{5/3} \;\alpha\; l^5$

e) Response acceleration as a consequence of the application of aerodynamic moment is proportional to:

$$\frac{M_A}{I} \quad \alpha \quad \frac{M}{Ml^2} \quad \alpha \quad l^{-2} \quad \alpha \quad M^{-2/3}$$

f) Drag of an airship, which may be equated to the thrust required for a given cruise speed, is proportional to area:

$$D \;\alpha\; l^2 \;\alpha\; M^{2/3}$$

From the above it is concluded that:

i) Applied disturbing moments are more or less directly proportional to airship mass.

ii) The rate of response to disturbing moments is inversely proportional to mass to the power of two thirds.

iii) Conversely the moments needed to restore an airship at the same rate are proportional to mass to the power of five thirds. The equivalent forces are proportional to mass to the power of four thirds. That is, as size increases proportionally greater control forces are required to maintain the same rate of response.

iv) The power required to cruise at a given speed reduces as size is increased to the power of mass to the two thirds. Thus, if at a given size, the power provided for cruise is just adequate to provide vectored thrust for control, as size is increased the installed power requirements are dictated by control considerations in proportion to:

$$M^{4/3} / M^{2/3} = M^2$$

Thus, whilst increase of size is a significant advantage in the reduction of relative drag and corresponding power needed for cruising flight, the converse is true if power is to be used to provide vectored thrust for control purposes.

FUTURE GROUND HANDLING SYSTEMS

Docking Systems

In recent years numerous proposals have been made to overcome what is still seen as one of the most problematical areas of airship operation. Many of these ideas must be dismissed as being wholly impractical and not worthy of further consideration. There remain a number of more promising concepts which, on the whole, are effectively developments of techniques used in the past. Almost invariably the proposals include some form of mooring mast, associated with a high level of automation to facilitate the docking process. Typically these ideas use either a mobile system based on some form of ground vehicle or a fairly elaborate fixed docking installation.

The mobile configurations are equipped with devices for automatically catching the airship as it flies over them. The devices proposed range from long prehensile arms, through winch operated cables to direct contact latch arrangements. In these latter systems the latch is inevitably located in the lower surface of the airship, resulting effectively in a near centrally located low level mooring mast. To be successful all these systems require the airship to fly precisely over the mooring vehicle at zero or very low relative forward speed. Most of the proposals are mechanically complex and would be difficult to engineer for large airships.

The fixed docking systems also demand precise control of the airship. Illustrative of the type of concept which has been put forward is that due to R P Gibbins (RAeS Symposium on Airship Design and Operation; Nov. 1986; Paper 18 - 'Support Systems for New Lighter than Air Vehicles'). In this proposal the airship is recovered by flying on to a turntable or mooring ring as shown in Figure 11.9. The craft is lined up by the engagement of a docking probe and secured by a mooring latch. The docking assembly is free to rotate to follow wind conditions. This idea can be combined with a rail transporter system to enable a number of airships to be handled at the same time.

Low Speed Control

As has been demonstrated the forces on an airship owing to atmosphere turbulence are large in comparison with its mass due to the inevitably low density and consequent large surface area. Motions from a steady condition can be rapid and of large amplitude. The counteraction of such motions demands the availability of correspondingly large control forces which have a fast response time. Clearly, conventional aerodynamic controls cannot meet this requirement, even if some form of gust sensing device is available to give advance warning. The conclusion is that the required control forces have to be provided by some form of internal power driving a 'thruster' system. Possibilities are:

a) Conventional propellers with reversing/vectoring facility. Such a system has both advantages and disadvantages. The primary advantage is that the basis of the system already exists for the purpose of forward propulsion. The disadvantages are the complexity - although with current technology this is far less serious than previously - and the power required. The thrust needed for effective low speed control is likely to be much greater than that needed for cruising conditions. Some alleviation of the complexity of vectoring might be realised by using separate power units for control in the heave, pitch and yaw modes. Variable pitch, reversing propellers are now conventional aeronautical devices.

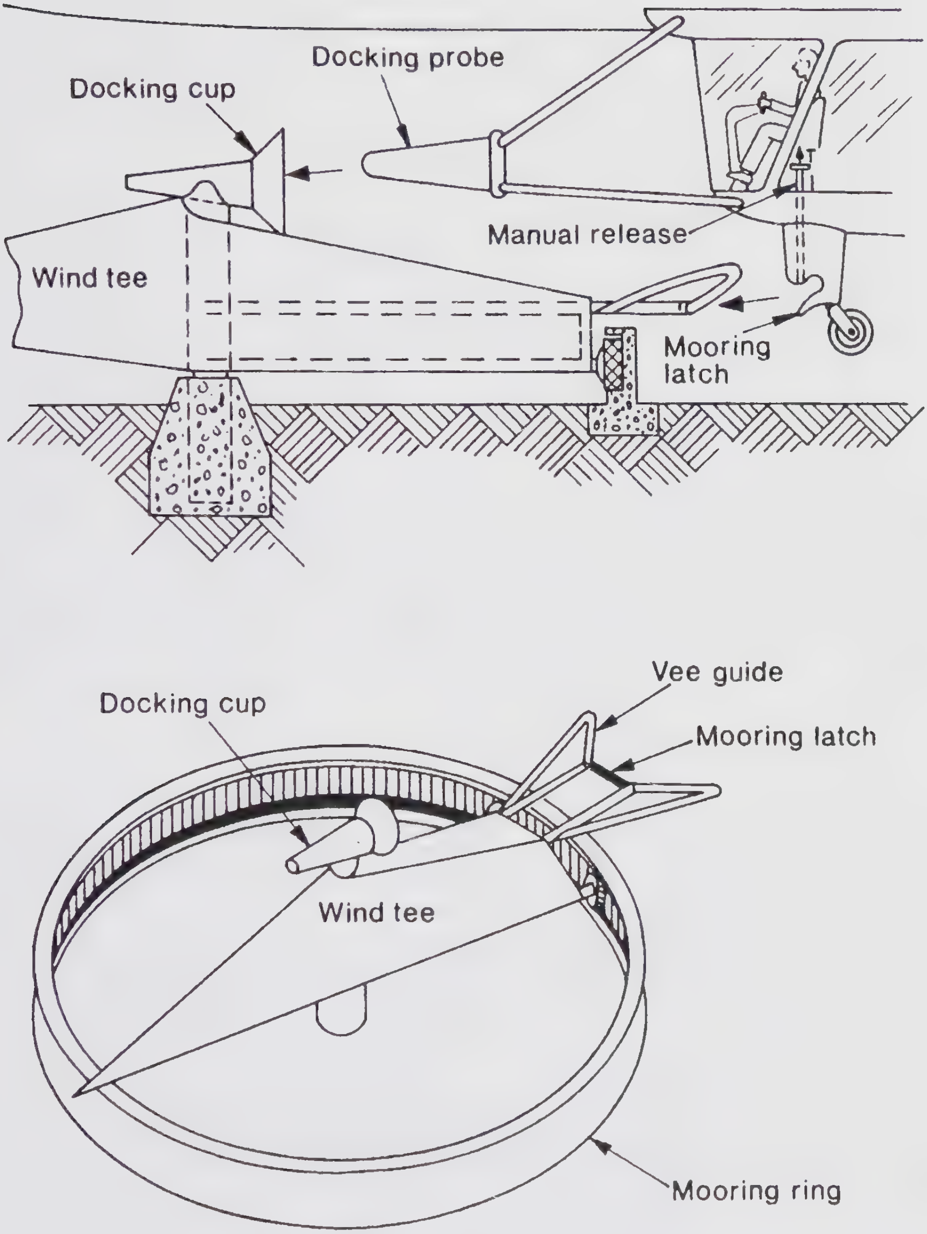


Figure 11.9. Automatic docking system (Gibbius).

b) Gas thrusters; such as rocket units, gas turbines or even compressed air jets. Rockets are capable of producing high thrust for short periods of time and may thus seem to be advantageous. They are, however, also potentially dangerous devices and not really suitable for routine operation. Gas turbines used to produce thrust are large and expensive in terms of the short time they are required for low speed handling. Compressed air jets tend to be inefficient in terms of power needed to produce a given thrust. Whilst a more detailed analysis of these possibilities could be undertaken the qualitative conditions suggest strongly that they are basically unsuitable.

c) Rotor Systems; which can be distinguished from propellers in two respects. Firstly, the disc loading is much lower, which results in much greater thrust force for a given power. Secondly, there is a potential for thrust-vectoring by use of cycle pitch control, as opposed to tilting of the driving shaft. The corresponding disadvantages are the relative large size and complexity, although there is no requirement for new technology.

Given adequate low speed control, various handling and mooring concepts become practical. These include both fixed and mobile mooring masts. Possibly the biggest remaining difficulty could be the procedure for moving the airship in and out of its hangar. It is thus desirable to minimise the need for the operation and correspondingly this suggests that the structure of the airship must be designed to withstand a reasonable probability of severe weather conditions whilst moored.

Loading and unloading Heavy Lifts

The mass of an airship can vary considerably according to the value of the payload and quantity of fuel on board. This complicates the handling of a conventional airship both on the ground and in the air and is particularly serious when the role of the craft is that of undertaking heavy lifts.

Whilst the airship is moored the problem may be managed without too much difficulty, providing there is no undue fore and aft movement of the centre of gravity. It becomes much more difficult when the requirement is for in-flight refuelling and, especially, when a heavy load has to be picked up or put down. A promising way of overcoming this problem is the adoption of a helicopter/airship hybrid concept. In this case the rotors are not only used for low speed control but also to provide overall lift to compensate for the payload and fuel. The aerostatic lift accounts basically for the empty mass of the craft and thus with a small adjustment the empty craft is actually effectively heavier than air. In fact it may be regarded either as an aerostatically augmented helicopter or an aerodynamically augmented airship. Since it is most likely that the disposable load is less than the empty mass, the latter description is more appropriate. The basic concept is not new. There was an attempt to integrate aerostatic and aerodynamic lift as far back as 1921.

More recently, the Piasecki Heli-Stat was based on the same principal. Unfortunately - in order to reduce development costs - each of the four rotors was derived from existing helicopters and crew responsibilities divided between all four. As might have been forecast this could have been considered to be a recipe for disaster. There was a fire in one of the helicopters, which was very unfortunate since the basic concept has much in its favour.

A more realistic approach with a fully automatic control system could be used to provide artificial stability at low speed as well as adequate control in all modes of operation. Some degree of gust alleviation to reduce structural loads should also be possible. Mooring/docking would be facilitated by closed circuit television although even this could conceivably be fully automatic. Such a craft might look like that depicted in Figure 11.10 (Howe D and Blythe A A - RAeS Symposium 'The Future of the Airship', Nov. 1975 - Paper 1). Although it would undoubtedly be expensive to develop, no technology is required that has not already been used on conventional aircraft. Because of the nature of an airship it could be that safe failure modes might be established without the need for the degree of software authentication and multiplexing necessary for an aeroplane.

CONCLUSION

The future solution of ground handling and mooring requirements is very closely associated with the provision of adequate control to enable precise low speed flight to be undertaken reliably and safely. Given this the remaining issues are concerned with ensuring that the structure of the airship is of adequate strength to resist the loading anticipated whilst the craft is moored.

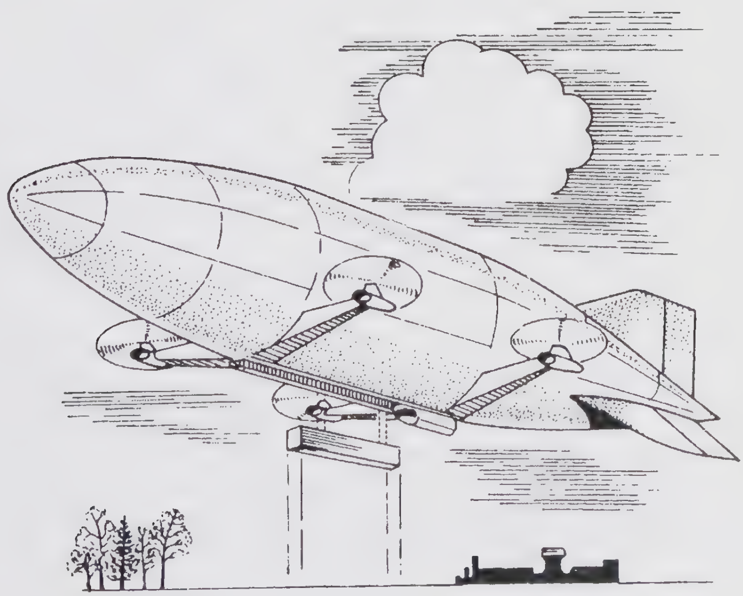


Figure 11.10. Possible hybrid airship concept - Heavy lift.

12

Piloting

D. Burns

INTRODUCTION

The piloting of an airship is a very special experience. It is also generally regarded as a very simple task - it must be, because the airship flies so slowly! Those passengers or guests lucky enough to have had the opportunity to steer their craft about the sky in the course of their flight would also tend to confirm that view.

In truth it is quite simple to fly the airship around the sky, provided that the pilot: (a) is properly trained and experienced; (b) has acquainted himself with the current and forecast meteorological situation; (c) has correctly loaded and ballasted the vehicle appropriate to the intended flight; (d) has performed a safe take-off; (e) is aware of the location of and is able to fly to the location of a trained ground handling party to achieve a successful landing; and (f) the airship has not developed any significant technical malfunction. In fact almost exactly the same requirements as for any fixed- or rotary-wing flight, the major differences being in less choice of landing sites, depending on the availability of a ground handling party and the possible greater impact of certain meteorological conditions.

Involvement with the training of airship pilots from many different backgrounds, indicates that pilots of rotary-wing and fixed-wing persuasions can make equally good airship pilots. Similarly, male or female pilots should be equally good candidates. However some pilots who have spent 20 years or more flying around at 400 knots may experience more than a little difficulty in adjusting to the low speed environment and indeed may never quite master airship flying. *Ab initio* pilots would benefit from at least some basic flying training in heavier-than-air craft, alongside which they will eventually have to operate.

Early in the conversion process, the pilot will benefit greatly from a short course of hot air balloon flying, where he (or she) would be introduced to the variations in low level winds, effects of local topography, gas management and of course the motions associated with buoyant flight. The student would also notice the dependence on the ground handling party. The would-be pilot would then be introduced to the other aspects of airship flying as described in this chapter. Most of these are straightforward, but the big emphasis on landing techniques and practice and also on meteorology will be apparent.

Every landing is different owing to a combination of factors: trim slightly different; static heaviness altered by fuel burn and/or superheat effects; wind velocity slightly varied; different eddy currents or thermals; slightly altered flight path, descent rate or ground speed. Many of these impact on others and combine to guarantee a different landing each time. Sometimes they will combine to make a safe landing impossible and the pilot must initiate a missed approach, which will be performed many times throughout his airship flying career and certainly much more frequently than in fixed- or rotary-wing operations. Throughout, however, the pilot must maintain a positive attitude that he can account for all of these factors and make a good landing. He can, of course, give himself a much better chance of success if he has chosen and executed a good approach.

The airship pilot has almost to become a part-time meteorologist. He will be much more effective if he can detect signs of a slight change in wind velocity, monitor development and movement of clouds, recognise conditions suitable for the development of temperature inversions or of local wind phenomena and so on. The airship would not be called vulnerable in many of these weather conditions, but operational effectiveness could be impaired.

The theory and details of how an airship works are covered elsewhere in this volume. The task of the pilot is essentially: to check that conditions are suitable for the intended flight; to detach the airship from the mooring mast; to set the ballonet air controls such that ballonet air may be exhausted as the lifting gas expands during the take-off and climb; to operate and manoeuvre the airship as required, maintaining envelope or hull pressure at prescribed levels; to set ballonet air controls to maintain envelope pressure during the approach to land - having due regard for any trimming effects; to execute a safe landing; and to assist the ground handling party in securing the airship to the mooring mast.

These operations and considerations are described in detail in the following sections. The techniques are valid for small and medium sized non-rigid airships up to about 20 000 m^3 volume. Non-rigid airships larger than this are likely to require amended techniques as they would exhibit different characteristics owing to the size, mass and inertia. Values of heaviness quotes are for a typical 5000 to 8000 m^3 airship and could be adjusted proportionately for larger or smaller airships.

Rigid airships will require different techniques owing to their greater options on ballast, mass, power plant and gondola (or car) locations, as did the great rigids of yesteryear.

EFFECTS OF CONTROLS

Airship control surfaces are generally very large in order to provide good control response down to very low airspeeds. Combining this with the very long control cable-runs usually required, means that control forces applied by the pilot on manually controlled airships can be quite high. The final load to be reacted to by the pilot can be modified significantly by normal aerodynamic means such as horn balances, balance tabs, etc. and by appropriate design of the pilot's control wheel, stick or pedals. Control loads may also be reduced by the installation of fly-by-wire or fly-by-light control systems with electric actuation of the control surfaces. On a moderate size of airship such as the Skyship 600, a delay of several seconds is very evident between control application and airship response being observed. This can be reduced slightly by the installation of powered controls which will also give the control deflection desired with no reduction owing to cable stretch and the like.

In normal flight more or less continuous control inputs are required to maintain straight and level flight - particularly on the rudder - on a normal day with turbulence and thermal activity. These will become less as the size and mass of the airship increase. In very smooth steady air such as that often encountered at night or over open water, only occasional small rudder inputs may be necessary.

A conventional airship with forward and aft ballonets can be trimmed in pitch to give level flight with no control load provided that the trimming ability is not limited by low ballonet contents resulting from the airship's flying at or close to pressure height. This is accomplished by altering the relative amounts of air in each ballonet, but note that the total amount of air will remain constant, provided that altitude and envelope pressure are maintained. The airship is then trimmed for this altitude and if disturbed in pitch, will return to the trimmed altitude by the normal automatic operation of the ballonet air system.

If climb or descent is required, the appropriate pitch angle must be selected by deflecting the elevator to give a pitch attitude and holding this deflection to overcome the pendulum effect which will tend to return the airship to level attitude. Releasing the pitch control would result in the vehicle returning to the previously trimmed altitude. The pitch load to climb or descend may be alleviated by valving or pumping air to/from the air ballonets, but note that the trim is only correct for one instant and that the process is continuous. On airships fitted with powered controls there may be an electrical means of reducing the artificial control load felt, but note that the ballonets will have to be adjusted to give final trim.

For an airship trimmed at steady airspeed and at up to moderate static heaviness/lightness, no change in airspeed will be recorded if that airship is established in a moderate climb or descent.

The rudder control generally requires quite large deflections initially to instigate a turn in the required direction at the desired rate. High yaw rates are possible but the airspeed will decrease owing to the increased drag, particularly at higher airspeeds. The airship will roll during turning manoeuvres to give approximately the correct angle of bank for a balanced turn. No rudder trim system is provided. The secondary effect of turning, which is a pitch down, will often be evident.

STATIC HEAVINESS

Static heaviness is a measure of the deviation from the state of static equilibrium or neutral buoyancy of the airship, usually measured in kg or lb. The airship is said to be statically heavy if it is heavier than air and said to be statically light if it is lighter than air. Airships normally operate within boundaries defined by a maximum static heaviness and a maximum static lightness.

An airship will make maximum headway under conditions of static equilibrium, since any lightness or heaviness must be supported by aerodynamic forces generated by incidence, which increases drag. The airship is generally flown slightly heavier than air as this is considered to make the task easier for the pilot in general handling and in particular, landing.

Heaviness can be considered to be:

(a) ballast, which has been requested by the pilot to be carried to make a particular task - usually landing - easier or within heaviness limits.

(b) payload, which could be jettisoned in case of emergency, e.g. fuel.

(c) weather effects, such as moisture on the envelope or super-heating of the lifting gas.

Most current airships operate with a requirement to be able to attain static equilibrium in major emergency situations, but airships larger than, say, 10 000 m^3 may not operate with such a requirement. Therefore the airship is loaded to static equilibrium conditions with payload and thereafter ballast is added to give the required heaviness. If part of the payload may be considered jettisonable, there is likely to be a reduced requirement for ballast where the jettisonable payload plus ballast would at least equal the static heaviness. In any case, weather effects must also be taken into consideration.

The static heaviness is thus known at take-off and the pilot should be continually aware of his (approximate) static condition so that he may react correctly in emergency situations, during manoeuvring and in preparation for landing. He can readily determine the current static heaviness condition by considering fuel burn, alteration in weather parameters and changes in payload, or by performing an in-flight weigh-off. To accomplish this he should ensure that the airship is in approximately neutral static trim and then bring the airship to a halt whilst maintaining a high envelope pressure. With the engines at idle power, the airship will then ascend or descend at a rate proportional to its static heaviness condition, which for medium-sized airships is found to be 200 ft/min per 100 kg static heaviness.

As heaviness increases it can pose additional problems. The take-off distance or cleared space to a standard 50-foot obstacle will increase significantly with increased heaviness as the airship must generate sufficient aerodynamic lift to support the heaviness. Vectored thrust can significantly reduce these distances but as heaviness increases, the actual power available from the engines becomes a major factor in determining maximum static heaviness. The consequences of a single engine failure during the take-off manoeuvre and acceptability of the consequences to the certificating or operating authority must also be considered. Still air conditions are of course the most critical and even a slight breeze makes a significant improvement.

If the airship can take-off safely in given conditions at a certain heaviness, it should be able to land under the same conditions. In conditions of static lightness, obviously no problem exists with take-off distance. Preparing the airship for take-off at the extremes of lightness may cause some problems. Landing distances will be considerably greater as the airship will have to be flying at an airspeed such that it can generate sufficient aerodynamic down-load to counteract the static lightness as it approaches the landing party (see 'landing' section). For vectored thrust airships, the same problems exist as with high static heaviness, except that the restriction on down thrust provided by the propeller may be the acceptable propwash/buffeting on the envelope.

As stated earlier, the maximum performance can be achieved with the airship at static equilibrium. Increasing power must be applied to maintain the same airspeed as static heaviness/lightness increases away from neutral buoyancy. These effects are slight at low values of heaviness/lightness, but show mostly at medium speeds and high values of heaviness/lightness. Indeed it may not be possible to maintain airspeed and altitude in these conditions, which may limit the planned operation.

Although the airship is normally flown heavier than air, the pilot should be careful to avoid flying excessively heavy during a mission with a view to providing ideal heaviness at the landing some hours away. This would give a higher fuel burn than if he planned to fly lighter with a lower fuel load, accepting a landing around equilibrium or statically light.

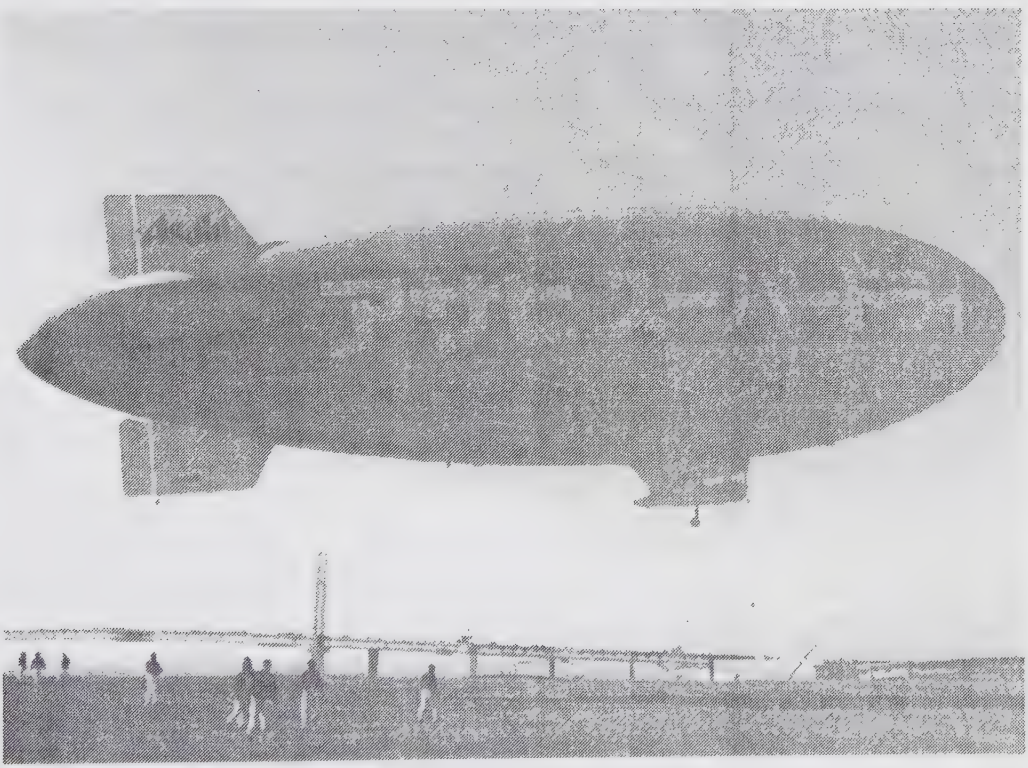


Figure 12.1. WDL-1 airship JA1005 on take-off from Yokohama, near Tokyo.

EFFECTS OF WIND

Owing to the low cruising speeds of airships, wind plays a very significant part in the overall performance and operation of the vehicle. Not all of the effects are negative however. Apart from the obvious benefits of a following wind, a moderate or strong wind can make the pilot's task easier in fixed station keeping and some manoeuvring, especially landing.

En route performance and payload range are obviously significantly affected by the wind. On current airships with typical cruise speeds of approximately 35 knots, a change of wind component by 2 or 3 knots can mean a doubling of ground speed. On airships with long endurance, the course steered between two points may be very different from that chosen by a vehicle with a much higher cruising airspeed as demonstrated by the pressure pattern flight paths of the old long range airships.

By climbing higher out of the turbulence layer a significant performance improvement may be obtained even though the wind-speed is higher. The drag effect of frequent large control deflections required to maintain course and reduce heading deviations can be greater than the wind-speed increase in this new layer. Recent developments in light, reliable LORAN and SATNAV installations can be used to great effect in determining the best altitude at which to cruise. There may also be a significant change of wind direction with altitude to be taken into consideration.

An increase in cruise speed, giving higher fuel consumption and hence reduced endurance, may significantly increase the ground speed to make a journey possible by reducing the effective headwind component. Consider the case of flying due north from A to B, a distance of 150 nautical miles with a wind aloft of 320°/20 kt. Typical fuel consumption figures for the Skyship 600 are used:

Table 12.1. *Cruise speed and fuel consumption*

	Cruise Speed (kt)	Fuel consumption (kg/hr)
a	30	25
b	40	40
c	50	70

The results would be:

Table 12.2. *Ground speed and fuel used*

	Heading	Ground Speed (kt)	Time (A-B)	Fuel Used (kg)
a	333°	11	13h 39m	341
b	341°	22	6h 49m	273
c	345°	33	4h 31m	316

Note that each 10 knot increase in air speed gives an 11 knot increase in ground-speed and also a doubling of ground speed by increasing air speed from 30 knots to 40 knots, which gives a lower fuel burn over the sector A-B.

A strong following wind can provide different problems, such as when flying cross-country with a ground support crew required to make the same journey. I once flew a significant portion of a 200 nautical miles cross-country leg with a following wind of 35 knots by turning round and flying into the wind at 25 knots to give the desired rate of progress along track!

A limitation on wind-speed for take-off and landing will be determined by the ability of the ground handling crew to manoeuvre the airship safely to and from the mast. Also, the maximum single engine airspeed of a twin engine airship should be greater than the maximum wind-speed for operating the airship, unless it is deemed acceptable to lose the airship if it suffers one engine failure whilst abeam or downwind of the landing site.

WEATHER

Each aspect of the weather has an effect on the airship in flight or on the ground.

Rain

The effect of rain on the airship is to make it heavier and hence reduce lift available, becoming in effect a part of the payload. This effect is produced in three main ways: the force of rain drops on the planform surface area, the moisture deposited on the airship and the reduction of superheat owing to evaporative cooling.

The force effects of light rain can be considered insignificant for all but the very smallest airships. As the planform surface area exposed to the raindrops increases with increasing envelope volume, so the total lift increase will be proportionately greater, more than cancelling out the effect of the greater area. For moderate and heavy rain, however, the effects are significant especially for airships at the mooring mast or flying at lower airspeeds. As speed increases the planform area becomes less significant as the raindrops would be striking more obliquely.

Even a thin layer of water over the envelope and tail surface area adds considerably to the mass, given the large areas involved. Fitting of a rain curtain (a small ridge or flap of envelope fabric attached around the hull) some distance down from the equator will deflect water off as it runs down the envelope, thereby preventing water lying on a significant portion of the envelope. Again, as speed increases, more water is drawn off. Typical values for a Skyship 600 airship may be 600 kg increase during heavy rain at the mooring mast, 400 kg after the rain has ceased and 150 kg after the excess moisture has been blown off. In flight, the increase in static heaviness may be 250 kg in heavy rain and 100-150 kg in moderate rain.

Any superheat present will be reduced as the moisture on the envelope is evaporated into the surrounding air. While rain is falling, the superheat value will be held down but could quickly recover when the rain ceases, depending on the ambient light level.

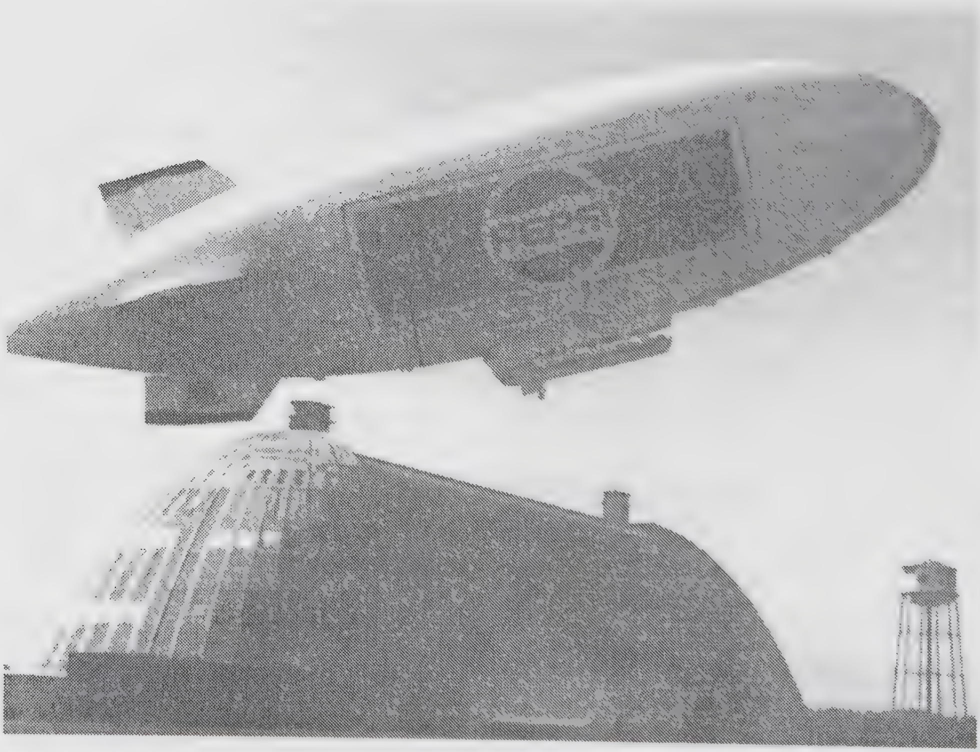


Figure 12.2. Skyship 600 G-SKSJ on take-off from Weeksville, NC, USA.

Inversion

Temperature inversions or indeed any significant variation from normal temperature lapse rate with altitude provide additional considerations for the airship pilot.

Consider first the case of a cool layer of air close to the surface with warmer air aloft, as may be found in winter anti-cyclonic situations, in valleys, or often during the hours after sunset on clear Spring or Autumn days. For the airship approaching to land in such conditions, it will suddenly behave as though it was statically lighter than calculated or as measured during the pre-landing weigh-off. With marked inversions, the airship may almost bounce off the top of the cool layer as the lifting gas shows a sudden apparent rise in measured superheat as the airship tries to enter the cool air.

To achieve the landing, the pilot should positively dive into the cool air and circle for a short while to allow the helium gas to cool down to the new environment temperature. If an immediate landing is desirable or the cool layer is quite shallow, either of the techniques later described for landing a statically light airship in light or calm winds may be used. Note that the airship will be becoming heavier during the manoeuvre and immediately after landing.

For an airship taking off in such conditions, it will suddenly appear to have increased static heaviness on leaving the inversion layer, which must be borne in mind when considering emergency situations or performance. The gas temperature, however, will quickly adjust to nullify these effects.

Often associated with these conditions is a region of relatively strong winds just above the layer, which may be blowing in a very different direction from the surface drift. Sometimes a layer of relatively warmer air can be encountered at several thousand feet above the ground. The wind velocity in this layer is likely to be different, which may assist the pilot in his task, but it may also contain more turbulence. The layer may also provide refuge from icing conditions in some situations.

Snow and Ice

If snow is encountered during flight, the pilot has several options depending on the type of snow. On flying through dry snow, very little will adhere to the envelope or other surfaces although some slight deposits may accumulate at certain aerodynamic stagnation points. Altering the flight path by pitching, yawing and changing airspeed occasionally should be sufficient to prevent any significant build-up.

On encountering wet snow, the pilot could climb to colder conditions to seek dry snow conditions or descend into warmer air in the hope that the precipitation will be in the form of rain at that lower altitude. Wet snow is much more likely to adhere to the envelope and control surfaces and will very quickly add to static heaviness. It is desirable to leave these conditions as soon as possible and an increase in airspeed will assist in reducing the amount of any snow adhering to the vehicle.

If snow conditions are encountered with the airship at the mooring mast, several methods are available - the most practical of which is to spray the envelope repeatedly with water or de-icing fluid solution. Removal of all ballast and reducing weight in the gondola will help to reduce the overall static heaviness of the airship under snow, but care must be taken to ensure that the airship does not then become top-heavy and topple. Snow should be removed from the top first and then equally down each side to prevent the airship becoming unbalanced.

Similarly, icing conditions should be vacated as soon as possible by climbing above or descending into warmer air. Ice may build up on the leading edges of fins which would require heating elements or pneumatic de-icing boots to remove it. The envelope may suffer from ice accumulations, some of which may be shed owing to the continuous flexing and alterations in internal pressure. This is also helped by flying at a higher airspeed.

Sunshine

The effect of sunshine is to superheat the temperature of the helium lifting-gas over that of the surrounding air, providing increased gas lift and reducing pressure height. The magnitude of the increase varies with the altitude of the sun, the transparency of the atmosphere and the airflow over the envelope. The colour of the hull is also a factor, from reflecting white and silver to heat absorbing black. The increase in lift is approximately 1% for each 3°C superheat.

Clearly the highest values of superheating will be found with a high sun, in clear air and with calm winds. Actual superheat will be reduced by smoke, dust, water vapour and clouds in the atmosphere. Typical amounts of superheat may be 6-8°C in Northern Europe to 10-12°C in North America. These values will be increased in calm wind conditions and will fall rapidly by 6-10°C as a cloud moves over the sun or a sudden light breeze springs up.

Superheat will be present even on cloudy days, although virtually negligible on a really dull day. At night, a slight degree of negative superheating may be evident as heat is radiated to atmosphere; this may be enhanced if the envelope is covered in moisture.

For flight planning purposes, the pilot will usually make an estimate of superheat for take-off, *en route* and for landing, taking into account the forecast weather conditions and time of landing, etc. These normal variations are unlikely to pose any significant problem for the pilot, except possibly in cases such as taking off late in the day with the intention of landing during the next day. In these circumstances careful calculation of take-off heaviness, fuel burn, likely weather and landing static heaviness will have to be made. The unusual step of valving some helium lifting-gas to return within the permitted range of static lightness for landing may be required.

During operations close to pressure height, the appearance of the sun from behind clouds or above the horizon would likely force the pilot to reduce altitude in order to maintain envelope pressure below upper limits owing to the increased superheat realised.

VECTORED THRUST

The development of vectored thrust has improved airship field performance and simplified the piloting task enormously. Used incorrectly however, thrust vectoring can vastly increase the work load on the pilot during the landing.

The ideal thrust vector system would be available through a full 360° rotation. Engineering complexity and, therefore, cost make this prohibitive, thus a typical range of +70°, -45° or +120°, -90°, measured positive angle of thrust line up from the horizontal would be employed. The degree of thrust vectoring required at any time varies with the airship regime of flight, static heaviness condition and wind-speed.

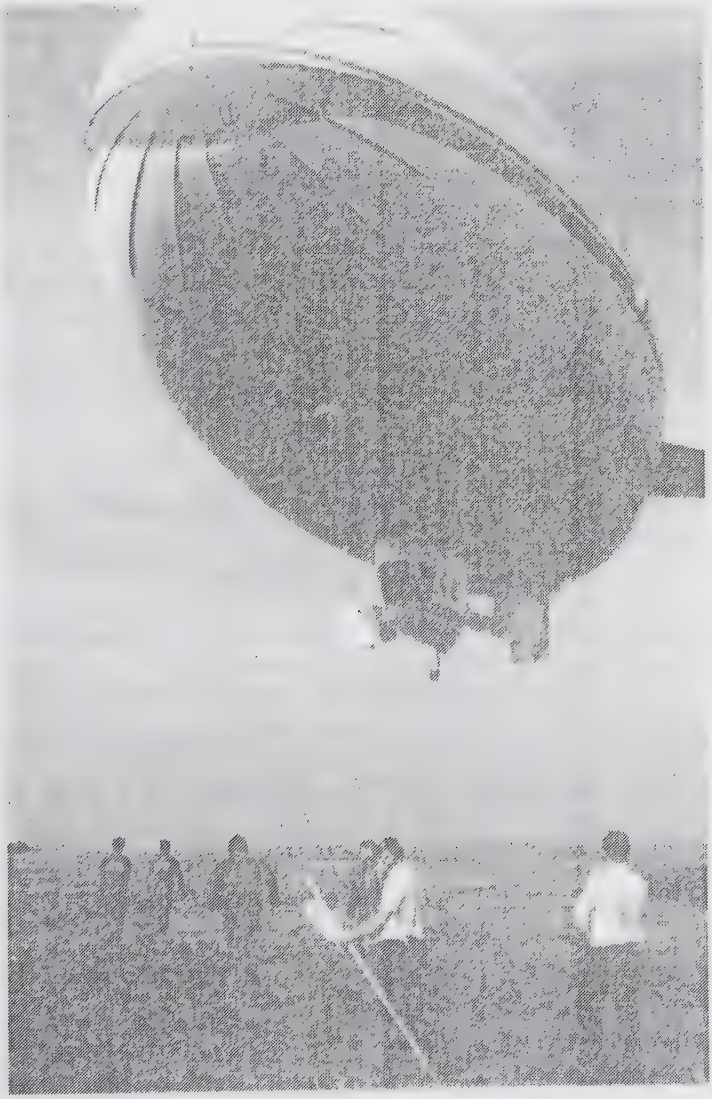


Figure 12.3. Skyship 500 G-BIHN landing in light wind conditions.

Ground Manoeuvring

Thrust vectoring is generally not used during the ground manoeuvring phase. During gusty wind conditions, however, when the airship is caught by a side gust, selection of a small amount of up vector (~15°) together with the normal application of power on the down-wind engine can assist in bringing the airship under control. After completing a statically light landing where down vector angle has been used to land the airship, the down vector selection may be retained in order to hold the airship in contact with the surface whilst ballast is loaded to take the airship to its normal slightly statically heavy condition for ground handling.

Take-off

An airship equipped with vectored thrust should demonstrate improved take-off performance over a similar airship not so equipped. The optimum angle of thrust vectoring from the horizontal for each type of airship would be determined from exhaustive flight tests and would in general depend on thrust available, engine thrust characteristics, static heaviness and wind-speed.

Cruise

Vectoring of the thrust is not normally used during the cruise phase of flight or for normal climb or descent. It could be used to enable a slow speed cruise to be performed where the airship static heaviness is too great to be supported at that airspeed. A portion of the static heaviness would therefore be supported by the vertical component of the thrust. Note that fuel-burn is higher in this condition than would be expected for the given cruise-speed. Similar actions could be taken to support a slow speed cruise in a statically light condition.

Vectored thrust could be employed for limited climb or descent where it was required to maintain a near level attitude or a particular low airspeed during a trial.

Landing

Landing is fully considered in the 'landing' section later. In general, vectored thrust allows a landing to be made into a smaller area than would be possible with a fixed thrust line and with a greater range of static heaviness. The task and effort required of the ground handling crew is similarly reduced.

Other Applications

If the airship is to be used for rescue work, collecting or depositing items on the surface or on a moving vessel or on any other similar surface, a high range of vectoring and reverse thrust should be available to the pilot. This would enable him to position reliably and very accurately, especially with the aid of a tail or bow thruster to counteract the effect of a side-gust.

Hovering

'Hovering', or, more correctly station-keeping is also much simplified on vectored-thrust airships. In conditions of moderate or strong winds and up to moderate static heaviness, thrust vectoring would not be required. In this event the airship flying speed equals the wind-speed and sufficient aerodynamic lift is created to overcome the static heaviness. As the wind-speed increases, so the static heaviness able to be supported also increases and similarly as the wind-speed drops, permissible static heaviness decreases. The flight angle of attack is varied to give the required vertical lift and the thrust is varied to match the wind-speed.

In normal wind conditions, an almost continuous workload of generally small attitude and power changes is required to maintain station accurately. Climbing out of a turbulence layer, say 2000 feet altitude by day and 1000 feet by night, is likely to give steadier conditions and a much lower or even a 'hands-off' work load may be experienced.

Lighter winds and/or greater static heaviness means that thrust vectoring would be required to remain on station. Again the airspeed must match the wind-speed and the vertical components of thrust must be combined with any aerodynamic lift of the airship to support the static heaviness. Note that higher static heaviness will require a higher power setting, burning more fuel; it may thus be possible to accomplish the same mission and give a similar condition of landing static weight by starting off with a lower static heaviness. With variable winds, the task can be quite demanding as with every change to power or vector angle, both the forward and upward thrust component will alter. The accuracy required will dictate the workload.

A non-vectored thrust airship may also hover in light winds, but if this were required over prolonged periods, alteration to static heaviness would be required. This would be done by accurate valving of lifting gas and/or dumping of ballast to maintain a condition close to neutral buoyancy. It may be that exact station keeping is not required, then the non-vectored airship may accomplish the task by performing slow orbits, increasing the variation of acceptable static heaviness.

GROUND HANDLING

During ground handling, the role of the pilot is to assist the ground handling crew or handling 'mules' to manoeuvre the airship safely from the mooring mast to the take-off location or to the mooring mast from the landing area. Appropriate ballasting/loading and trimming will have been performed or requested by the pilot to assist this manoeuvre to be carried out safely under the control of the ground crew chief.

In conditions of light or calm winds, the flying controls will be ineffective and slight assistance may be given to the ground handling party by the use of idle/differential thrust on multi-engined machines. The task of the ground handling crew will also be relatively easy in this condition. When the wind is moderate and relatively straight, assistance may be given by the pilot using the flying controls and with some thrust applied to prevent the vehicle slipping rearwards.

With increased wind strength, the airship may be considered to be flying and even small control movements will give significant motions. It is important that the pilot selects power to match the wind-speed experienced, or the forward thrust required to maintain station and move ahead will have to be provided by the external handlers. Insufficient power application on some models will be characterised by a nose down attitude instead of the normal level attitude and/or the airship slipping rearwards. As is the case in the air, there is a delay of several seconds between the pilot's applying a control movement and the airship's responding, so care must be taken to avoid the pilot's actions moving out of phase with the ground handling crew chief's demands. If the nose is allowed to rise, the wind may well lift the airship out of the hands of the ground handling crew, at which stage the pilot may elect to complete a take-off in the interests of safety. Similarly, if the nose is allowed to drop, it may be forced down further by the wind and so preventing a safe take-off being achieved.

In turbulent or gusty wind conditions, great concentration is required by the pilot in synchronising power application and control inputs, while remaining alert to any external advance warnings of approaching wind change or gust which may be signalled across the water, or by dust, smoke, flags, trees or other cues. The airship may be lifted up or be moved rapidly sidewards such that the ground crew chief or pilot considers it would be better to release control of the airship to the pilot. The pilot then performs the 'emergency take-off' manoeuvre by applying take-off power and possibly selecting up-vector (on airships fitted with vectored thrust) and dumping ballast.

The same considerations must be employed after landing, with the room for manoeuvre or error being much reduced as the obstacle of the mooring mast is approached. A mobile mast, that is a mooring mast attached to a vehicle, which will be later tied down at the desired location, can greatly reduce the time spent in this ground manoeuvring phase.

If the airship does encounter a side gust, full rudder and high thrust on the downwind engine should be applied to bring the nose of the airship back into the new local wind. Sometimes the ship may move a considerable distance before it can be re-aligned with the wind and the installation of a bow thruster or, preferably, a tail thruster to pull the stern round out of the wind would give a huge boost to ground handling procedures. This could easily be arranged to work in conjunction with the rudder by a selectable low speed switch or similar device.

TAKE-OFF

An airship employing vectored thrust should exhibit superior take-off performance to that of a similar airship not so equipped.

The take-off manoeuvre can be considered to commence once the airship has been ground-handled into the desired position and the pre take-off vital actions performed. The methods of take-off are the rolling take-off, the vectored take-off and the 'up-ship' take-off, which will each be considered in turn.

Rolling Take-off.

Airships not equipped with vectored thrust must use this or the 'up-ship' method; even those that are equipped with vectored thrust may sometimes use this technique.

The airship starts as always aligned with the wind and the pilot applies power to commence the take-off roll. The initial track of the ship over the ground may be controlled by the ground handling party until they release the handling lines. The rate of power application and track of the airship over the ground will depend on the airship configuration, wind velocity and take-off path available. The take-off run will continue until the total aerodynamic lift generated by the airship vehicle equals the static heaviness; the airship will then be flown off by raising the nose a little way, either by careful selection of elevator or by releasing air from the forward ballonet to give flying incidence. A statically light airship will generally be released by the ground party and power applied as it floats skyward.

On a conventionally configured modern airship, the rate of power application must be controlled to prevent a tail-strike owing to pitch-up induced by a rapid application of thrust. Very light wind conditions are obviously the most critical but with increased wind-strength some power would already be selected just to remain stationary and the elevator control would start to become effective; this would both reduce and control any pitch-up. This allows a more rapid application of power and a significantly shorter ground run. As the airship lifts off, the pitch angle must be carefully controlled in the initial stages again to prevent the tail striking the ground. The significance of the pitch-up is obviously less with short airships or with those employing an X- or inverted Y- tail configuration. A tail wheel or similar device can also help.

The take-off run path should ideally be smooth and into wind; but with practice, experienced pilots can use a smooth surface not aligned with the wind whereby the drift angle is controlled by rudder to track the airship down the desired path. If a runway is being used, care must be taken to ensure the handling lines do not snag on any lights or similar obstructions.

Airships equipped with vectored thrust may occasionally use this method for take-off. There is a greater risk with a rolling take-off as the vehicle is exposed and vulnerable to side-gusts and down-draughts during the prolonged ground run. Certification of some airships employing this technique can be quite complex owing to the number of variables involved, primarily the rate and stage of power application causing difficulty with scheduling of take-off distances. Actions following engine failure during the take-off run are also very dependent on many variables.

Vectored Take-off

This method is almost always used by airships so equipped. Once the airship is in the desired take-off location, the appropriate vector angle is selected, power applied and as the airship lifts off the ground handling lines are released. The nose of the airship may be pulled to one side by the ground crew after lift-off using the nose handling lines to optimise the climb out direction. The vector angle selected will be determined for each airship type from exhaustive flight testing and will ideally be scheduled with prevailing mean wind-speed. Flight testing will also determine the optimum point in the manoeuvre to reduce vector angle and power.

On the Airship Industries Skyship 500/600 series, the optimum vector angle for take-off is 45° with static trim angle at 0°. At vector angles less than this the airship pitches nose up on application of power and from moderate heaviness upward, is slow to leave the ground; the airship will then sink in case of single engine failure. At vector angles greater than 45°, the airship leaves the ground cleanly but the nose gradually pitches down and the airship is slow to accelerate - both causing a poor take-off performance. On the Loral GZ-22, a much lower vector angle is employed which uses the high power available to great effect by powering off the ground and accelerating.

Vectors are returned to the horizontal in one motion as the airship attains sufficient flying speed (approx. 22 knots in Airship Industries vehicles) to generate aerodynamic lift and this action causes the airship to pitch nose-up to the optimum climb out attitude. Increased wind-speed will reduce the time to attain flying speed and distance travelled while that is achieved. During take-off at the (ground handling) limiting wind-speed of 25 knots, the standard technique is still used and the vectors are returned to horizontal almost as soon as the airship leaves the ground.

On the Airship Industries vehicles, if an engine failure occurs during take-off before passing directly over the ground crew chief, who stands under the nose of the airship, the take-off is abandoned and the airship allowed to return to the ground - possibly jettisoning ballast and selecting higher vectored thrust angles to cushion the landing using live engine power. The ground handling crew must then regain control of the airship. If engine failure occurs after passing over the crew chief, the take-off is continued, possibly dumping ballast and reducing vector angle to zero at the normal cue before positioning for landing.

'Up-Ship' Take-off

This method requires the gondola or car handling ground party to thrust the airship into the air from a standing or low forward speed start. The gondola may be thrust directly upwards and released or bounced several times on the undercarriage before one final effort is applied to thrust upwards. It is only really practical at low to moderate static heaviness and the pilot must apply full power as the airship is travelling upwards and then climb away. As power is applied and the nose pitches up, elevator is selected to control the pitch-up which also gives added lift to the tail. If the airship begins to sink towards the ground the nose must not be held up, as would be the immediate reaction of a fixed-wing pilot, but an approximately level attitude should be maintained. This allows the airship to bounce on the sturdy undercarriage without striking the tail before flying off as described earlier. Similarly, if an engine failure occurred during the manoeuvre it is likely that the vehicle would descend and contact the ground, bouncing in a controlled level attitude before flying off. As the wind strength increases the performance improves significantly.

PRESSURE HEIGHT (ALTITUDE)

Pressure height (or pressure altitude) is that height or altitude at which all air ballonets are empty and the envelope pressure can no longer be controlled by the valving of ballonet air. The envelope pressure will normally also indicate a higher than normal value.

A significant climb above this height will cause a loss of lifting-gas and hence lift owing to the operation of the automatic envelope pressure relief-valves as the pressure increases through the high pressure warning setting and to the gas pressure relief-valve setting. The gas may be valved manually to permit operations at around pressure height. The climb to pressure height is normally performed with the ballonet damper-valves closed, especially as pressure height is approached as indicated by a higher than normal envelope pressure and ballonet manometers or pressure gauges showing a lower pressure than the envelope pressure.

The pressure height attained initially is likely to decrease after a short period as the lifting-gas warms up after its adiabatic expansion during the climb. It is quite possible to operate at and around pressure height for long periods, although the work load may be higher owing to out of trim control forces as no trimming is available (ballonets empty). Greater attention is required to altitude keeping in order to prevent a climb through pressure height, resulting in the automatic valving of lifting-gas or repeated operation of the gas high pressure warning signal.

In operational service, a climb to pressure height is regularly performed to give the most accurate value possible of the volume of gas contained within the envelope, which, over a period, will indicate the condition of the envelope. At this time, a check should also be made - through the envelope viewing-dome - of suspension-cable geometry and attachments as well as the envelope-fabric for holes or perforations. For comparison purposes, the pressure-altitude should always be recorded, that is the reading of the altimeter with the subscale set to 1013 mb. or 29.92 inches. Gas temperature should also be recorded at this time to enable a calculation of the standardised gas volume to be made for payload check and comparison purposes. Note that a high lifting-gas volume will give a high payload capability but a low pressure altitude, reducing with increasing ambient temperatures. Reduction in lifting-gas purity for a given volume will also reduce payload capability.

The static trim angle at pressure height is of interest in the design and certification stage of the airship in confirming centre of gravity and loading calculations. If the static trim angle is nose high, a heavy airship should be allowed to descend before power is applied to fly away so that the airship does not climb through pressure height. A statically light airship should be recovered to flying speed immediately. Note that application of power on a conventionally configured airship will cause the nose to pitch up further.

FREE BALLOONING

If an airship suffers a total propulsion unit failure in flight, it should be operated as a free balloon. This means that immediate steps be taken to preserve envelope pressure and to dump ballast or lifting-gas to adjust static heaviness to near neutral buoyancy. Some particular situations may require an immediate climb to avoid obstacles, say, so the requirement would be to adjust first to statically light and then to neutral.

When altitude and envelope pressure are under control and the pilot has determined that the immediate track downwind is acceptable, he should try to determine the cause of failure and re-start the engines. Assuming that this meets with no success he must assume that an eventual free balloon landing will be required. He may want to fine tune the static heaviness or change altitude to take advantage of a different wind strength or direction, to escape turbulence or to descend below a cloud layer ahead. The airship will drift with the wind, usually side on to the wind.

Superheat and hence static heaviness are likely to change during the free ballooning. Superheat is initially likely to rise as the airship is now travelling with the wind rather than through it, so that the cooling effect is now removed. Fluctuations in superheat owing to clouds moving across the sun will be manifested as changes in static heaviness which would usually require no action provided that they caused slow climb or descent and lasted a short time, otherwise gas or ballast would have to be jettisoned accordingly. Note that the pilot is unlikely to be able to tell if the hull is receiving direct sunshine or not, unless he watches any shadow on the ground.

If the airship was flying in precipitation immediately before the engine failure, additional static heaviness will be observed owing to the build-up of moisture and also to the force of the droplets impacting on the large airship surface area. Typical values for this effect when flying in moderate rain may be 200kg for a 4000 m^3 envelope, 300kg for a 7000 m^3 and 400-450kg for a 10 000 m^3 envelope. Low-level turbulence and thermal activity can also combine with the above effects to give a confusing signal to the pilot.

In conditions of very light or calm wind and with favourable terrain, it may be possible to wait while the ground handling party re-position to enable a reasonable landing to be effected. Normally, however, the pilot would have to look ahead downwind to select an area where it may be possible to conduct a free balloon landing with minimal external assistance. An ideal area would be a large open area, with no power lines, poles or similar obstructions and a broad line of trees running perpendicular to the projected wind direction at the far end. The distance downwind for this area would vary with the wind strength and altitude, both factors dictating a required rate of descent.

Descent would be initiated by valving the lifting gas to make the airship statically heavy to give the required rate of descent which will take some time both to stabilise and to arrest. For example, if $100m^3$ of gas were released, this would make the airship statically heavy by 100 kg and give a rate of descent of 200 ft/min. After dropping 100 kg of ballast to return the airship to static equilibrium, it will descend a further 100-150 feet before levelling off, all other factors excluded. Rates of descent should be kept low such that envelope pressure and hence envelope shape can be maintained by the battery-powered ballonet fans.

As the airship nears the ground and approaches the touchdown area, a drag or kite line with attached ballast bags may be lowered, with the one end attached securely to the gondola structure. This line will have the effect of reducing the static heaviness and hence rate of descent as the ballast touches down and also act as a drag. The effectiveness of this will be considerably reduced in a strong wind and so should not be employed. The aim should be to touch the airship down just short of the tree line which should act as a barrier to help prevent the airship's continuing on down wind. The envelope pressure is likely to fall to quite low values in the final stages but this is of no consequence. The airship should be electrically dead before landing to minimise risk of fire.

When the airship is in contact with the ground, passengers and crew should be evacuated on the upwind side, at the same time pulling the envelope rip line and lifting gas dump valves. The drag line or available handling line should be attached to any suitable anchor point to assist in restraining the airship. In low wind conditions, it may be possible to avoid activating the helium rip line and instead tether the airship until further ground help arrives.

It is unlikely that significant useful help could be summoned by radio if the attendant ground crew are unable to assist. The limited battery power should be used to power the ballonet fans to maintain envelope pressure, for the ATC transponder and for only brief RT calls to any major airports or emergency service units.

LANDING

The technique employed for landing the airship will be dependant upon many factors including space available, obstacles, wind velocity, static heaviness and availability of vectored thrust. Two main techniques are available to the pilot: aerodynamic and vectored landings. The required result is the same, i.e. to present the airship to the ground handling party close to the ground with low or zero forward, vertical and horizontal velocities and approximately in level trim.

In practice, the airship will often land with some velocity owing to wind or static heaviness conditions as described later and a combination of techniques will be used. Many pilots will also develop their own modifications to the following basic techniques.

Aerodynamic

This technique must be used on non-vectored thrust airships and may be used by others. Trimming is a very important factor in achieving a successful landing using this technique. The airship is deliberately trimmed nose heavy in the case of a statically light airship and (to a lesser degree) trimmed nose light in the case of a statically heavy airship. This causes the airship to behave as if it were heavier than the actual static weight in the statically light case, enabling a lower approach speed to be used than that which would otherwise be required. Similarly, a statically heavy airship would behave as if it were lighter than the actual static heaviness.

As the airspeed reduces, aerodynamic control is lost and the airship attitude alters only slightly to that of the statically trimmed condition which aids the landing in each respective case. Clearly, the amount of trimming away from the horizontal must be limited by the requirement to maintain adequate ground clearance for the nose or tail once the vehicle approaches the ground. Note also that the use of reverse thrust to reduce the airspeed will cause the nose to pitch down further on a conventionally configured airship.

In practice, the airship will normally be landed with only slight static heaviness, dumping water ballast as required to achieve that condition. Lifting gas would not normally be valved to reduce static lightness. The exact technique will vary with the prevailing wind conditions as detailed.

Light or Calm Winds

With these conditions and a statically very heavy airship, the field length requirement will be at its greatest. Aerodynamic control and hence airspeed must be retained whilst the airship is flown down close to or onto the ground before reducing airspeed as much as possible to facilitate the ground handling party's task. If the airship descends towards the ground, the pilot must allow it to bounce on the sturdy undercarriage and not try to hold it off by raising the nose, the result of which would surely be a tail-strike. As stated above, normally - in these conditions - water ballast would be dumped to reduce static heaviness. With decreasing static heaviness, so the approach speed can be reduced to just a few knots at static equilibrium. The low rates of descent generated by low static heaviness after the loss of aerodynamic lift can easily be absorbed by the landing gear e.g. a 50 kg statically heavy airship will accelerate to 100 ft/min rate of descent.

In these conditions, the inertia of the airship shows particularly well. After selecting power to flight idle, only a very slow reduction in airspeed/ground-speed will be observed and a great deal of anticipation is required in order to have the ground speed reduced before meeting the ground handling party. The differences in inertia between a 5000 m^3 and a 7000 m^3 and between a 7000 m^3 and a 10 000 m^3 vehicle are very marked.

As static lightness increases, so approach speed must be increased again so that sufficient negative lift may be generated to hold the airship down on the final stages of the approach, in association with the nose heavy trimming as described earlier. The limitation on landing static lightness may well be defined by the maximum out of trim angle that is acceptable for landing in these calm winds.

During approaches in these conditions, the airship may be hit by a thermal, a wind switch or a significant side gust that will necessitate a missed approach or go-around for the pilot to try again.

Moderate Winds

This is probably the pilot's favourite wind condition and he/she can approach at a reasonable airspeed giving good aerodynamic control, enabling him to accomplish a successful landing throughout the heaviness range of his airship. If unsure of the correct power setting during the approach, the power levers should be set to idle to see how the ground-speed/airspeed alters and the power adjusted from there. For example if the airspeed reduced to 15 knots with zero ground speed, power must be selected to give an airspeed of slightly greater than 15 knots to approach the ground handling party and then reduced to the 15 knot value as the ground party is reached. Frequent small adjustments to power should not be necessary. This same final power setting will be approximately correct for maintaining station on the ground.

The degree of trimming to compensate for extremes of static heaviness or lightness should be reduced over the light wind case as the controls will remain effective throughout and it is not desirable to hold a mis-trimmed ship in such a wind if at all possible. The inertia of the airship is not as apparent as in the light wind case.

Strong Winds

Under these conditions good aerodynamic control is available throughout the approach up to and including the landing. A truly vertical landing throughout the range of heaviness can be performed using small attitude changes to adjust the rate of descent once the wind-speed has been matched by selection of the appropriate power.

Vectored

These techniques are generally used by pilots on vectored thrust airships, in preference to aerodynamic techniques. The vectored range available and any associated power limitations may affect some procedures.

For landing in any wind condition - except for a vertical landing - a very successful and well-proven method is to establish a selected approach path and to fly towards the ground handling crew, maintaining the same perspective as one would with PAPIs or VASIs for a conventional runway. This can be employed with shallow, normal or steep approaches, at various speeds, having due regard for obstacles on the approach or limitations of the airship system e.g. performance of the ballonet air system limiting the rate of descent. The rate of closure with the landing position should be monitored carefully, bearing in mind that this rate ideally should be very low on reaching that point.

Calm or Light Winds

For an airship approximately at equilibrium, vectored thrust would not be required and the main aim would be to fly down to the ground crew and ensure that ground speed is low at the time of capture by them. An airship equipped with reverse thrust could approach faster and reduce speed later on the approach, but if this was not available then the correct airspeed would have to be established early on during the approach, having due regard for the inertia of the particular airship. Some pilots may elect to use a small up-vector angle combined with reverse thrust in the final stages to accomplish the landing.

As static heaviness/lightness increases from equilibrium, so the appropriate up/down thrust must be provided by the engines with the vector angle such that the forward component of thrust gives the desired low ground speed. It is with calm winds and towards maximum static lightness/heaviness that the requirement for more than 90° of vector angle availability is demonstrated best. 120° is desirable to enable a small retardation force to be applied or to permit a burst of power to arrest a descent without giving a forward acceleration. Again, the static heaviness may be reduced by dumping water ballast and the static trim should be neutral.

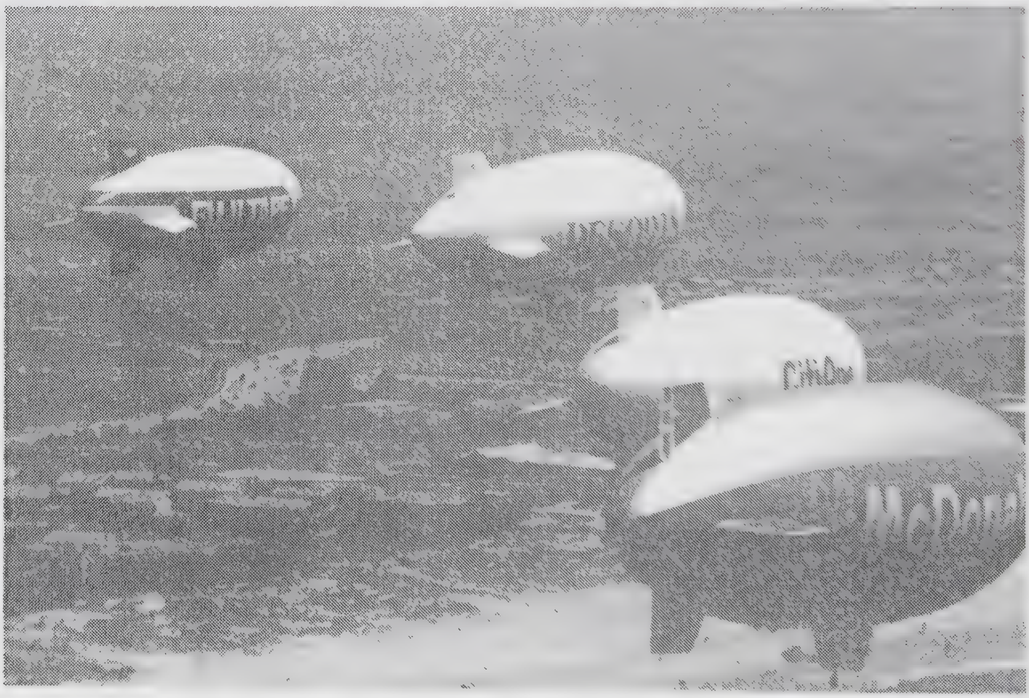


Figure 12.4. An airship formation flight over long Island, New York, July 1986.

Light Unsteady Wind

In this wind condition, the use of differential thrust to oppose side gusts and control the approach path is desirable, as the rudder will not be very effective at the low approach airspeeds. At approximately static equilibrium, the pilot would elect not to use the vectoring system and land as previously described, prepared to apply bursts of power to counter any yaw or lateral deviation during the approach. Reverse power may also have to be used to assist in opposing the yaw and thereafter to reduce the airspeed. Short asymmetric bursts of power should not give a significant airspeed rise.

As the static heaviness/lightness increases, so a greater vector thrust angle away from the horizontal must be carried to support this increase. The forward component of thrust normally required will be low as dictated by the requirement for a low approach speed, so the vector angle is likely to be large, if permitted or obtainable. On encountering a side gust, the angle must be reduced as power is applied to counter the deviation, possibly selecting reverse thrust on the opposite engine. For the thrust alteration to have the desired effect, the vector angle must be reduced smartly below 30^0 with a significant increase in power required. If the gust was sensed early followed by an immediate reaction, the deviation may be quite small. In other cases, it may require the pilot to go-around. Caution should be exercised when applying high power settings with down vector angle selected while close to the ground.

The fitting of stern- or bow-thrusters would greatly simplify and improve the close-in handling in these conditions. An airship of increased mass would be less affected by a given gust.

Moderate Winds

As before, this is the pilot's favourite wind. If the airship is close to equilibrium, it is likely that no vector deflection would be employed. Some pilots prefer, however, when slightly statically heavy to land with some positive vector angle selected and to oppose this with nose-down elevator giving the opportunity of a more expeditious go-around if required.

Consider now the statically heavy case. As the airship is flown down the chosen approach path, the airspeed is being reduced as before to give a reducing ground speed with the aim again of low or zero forward speed on reaching the ground handling party. With reducing airspeed, aerodynamic lift is lost, increasing the rate of descent, and can be compensated for initially by raising the nose. But as speed reduces further, the static heaviness has to be supported by a vectored thrust component.

With constant power, selecting up vector will reduce the forward thrust but give a vertical component upwards. The pilot must continually assess the descent rate and ground speed, adjusting power and vector angle setting as required. For the landing the airship will have a moderate to high vector angle with a power setting to maintain a forward thrust component to match the ground wind-speed. Note that from a stabilised approach, selecting vectors progressively to 45^o or 50^o in three stages, with constant power set, will give a reducing forward component with increasing upward component; fine tuning of descent rate is available by elevator.

If a vertical landing is required, the airship should be brought over the landing site and allowed to descend vertically by adjusting power and vector angle, ensuring sufficient forward component of thrust to maintain the ground position. Slight adjustment to the descent rate can again be provided by attitude adjustments. Vectors should be returned to the horizontal on touchdown and power adjusted to match the ground wind-speed.

For the statically light case, a mirror image of the same procedure is used. As the airspeed is reduced during the approach, lowering the nose by elevator will initially maintain the descent rate, followed by selecting and varying the down vector angle and power setting to give the correct vertical and forward speed.

Strong Winds

For a wide range of heaviness/lightness the pilot is unlikely to use the vector control as the elevators will give quite crisp pitch control; a large forward thrust component will be required. The effects of inertia will not be very noticeable and the airship will respond to changes in power from the datum high approach setting.

Towards the top limits of heaviness/lightness vectors will be used as in the moderate winds case but only small angles, say up to 30°, will be required owing to the high power settings employed. Again, on landing, it is important that vector angles are reduced to zero and power maintained to match the ground wind-speed.

13

Performance

R. Hunt

MISSION CONSIDERATIONS

The payload limitations of heavier-than-air (HTA) aircraft are, in most cases, imposed by airfield field performance and weight, altitude, and temperature limited climb considerations. In contrast, the payload of airships is generally limited by the gas lift available in the climatic conditions prevailing at the cruise flight altitude. This means that the key cruise altitude, temperature conditions, payload and mission profile must be established very early in the design process, as alterations to these can cause big changes to volume. Only at extremely short airfields does take-off performance become a limitation. Other comparisons with HTA are as follows:

- Airship engines operate normally in a different power regime to HTA craft and manufacturers quoted SFCs are often not reliable.
- Power offtake to drive accessories and mission equipment has a far more significant effect on LTA than on HTA.
- Engines and propellers 'off the shelf' are normally optimised for the considerably higher speeds of HTA.

This chapter attempts to explain these differences and show ways to circumvent them. Points of difference that are known to have caused misunderstandings are dealt with first.

MAXIMUM 'IN-FLIGHT' FUEL USAGE

The maximum fuel that can normally be used 'in-flight' is limited by the difference between take-off heaviness and landing lightness.

The take-off heaviness is a mass greater than equilibrium. This heaviness will (for a multi-engined airship following an engine failure at the critical point) allow the airship to climb without any loss of height at any point in the flight path up to 50 feet. This heaviness may be further limited by the structural maximum heaviness or by a field length limitation. With modern ZTOL airships, the critical point is normally accepted as being the point at which the pilot passes over the crew chief's head.

Maximum lightness is that given in the flight manual. It is usually lower than equilibrium and is above the lightness at which the airship ceases to be easily controllable by an average ability pilot, with special emphasis during the landing phase.

This value - for the amount of fuel that normally can be used - could be increased by incorporating a water recovery system to the power plant on piston engined craft. Water then replaces some or all of the fuel mass used. Theoretically, by incorporating such a system, it should be possible to take-off and cruise at any speed up to maximum and maintain equilibrium. In practice, however, such a system has a high power consumption because it is heavy (or, in the case of some previous radiator installations, has a high drag). It is also very expensive to develop and certify. With the technology available at the time of writing, it is probable that the designer will elect for a design such that the ship can take-off at maximum heaviness and then cruise at maximum continuous power. The recovery system would then be operational but not capable of recovering 100% of the fuel used. Its performance would be sufficient for maximum lightness to be just reached when all the fuel that can be carried in the design case is used. It is also the worst case. When cruising at lower speeds, maximum lightness need not be reached. This is because, as engine power and hence fuel flow decreases, a greater percentage recovery will occur until 100% recovery becomes possible at some design power below MCP.

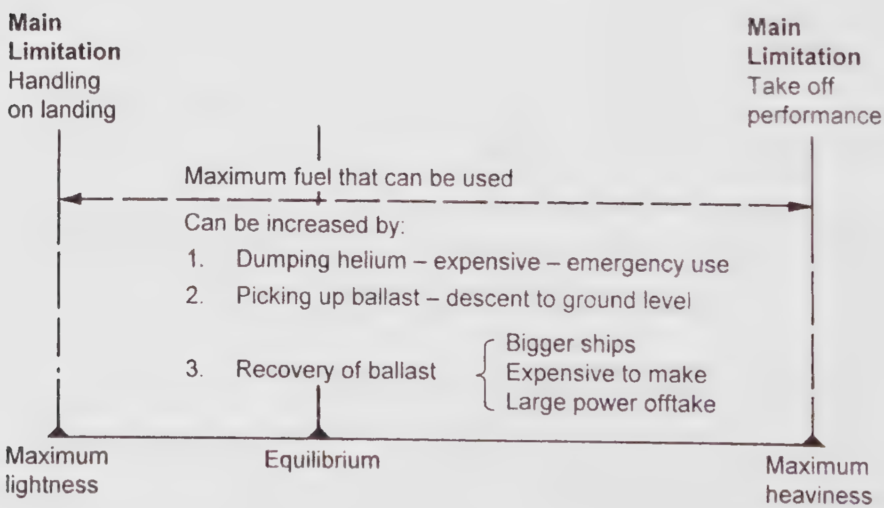


Figure 13.1. Maximum in-flight fuel usage.

Owing to the high mass flow and low water in suspension in a turbine engine exhaust, insufficient water can be recovered to make this a practical proposition

An alternative to water recovery is to descend to surface level and pick up ballast. This, depending on the mission, may not be acceptable operationally.

In an emergency, helium dump may be used to decrease lightness. This is a very expensive option and should not be considered for normal use.

Innovations in forms of propulsion, such as solar energy or fuel cells, may in the future overcome this problem as they mature and become of comparable or lower weight compared with conventional power units,

Figure 13.1 summarises these points, providing the load sheet allows at least the sum of maximum heaviness and maximum lightness to be carried as fuel.

ENGINE SELECTION

Airships normally have a far greater range of power required for propulsion in level flight than heavier-than-air craft. This presents problems for the performance engineer in selection of an engine for an airship. Specific fuel consumptions quoted by engine manufacturers are based on heavier-than-air requirements, where, except in circumstances such as power-off descents, 'in flight' power is usually in excess of 50% of take-off power. Manufacturers normally quote the SFC for either maximum cruise, maximum continuous or for take-off power (TOP). MCP will normally be at least 80% of TOP. Figure 13.2 shows that there is little difference between the SFCs at these two ratings, and relatively small differences over the full power range for the HTA machines.

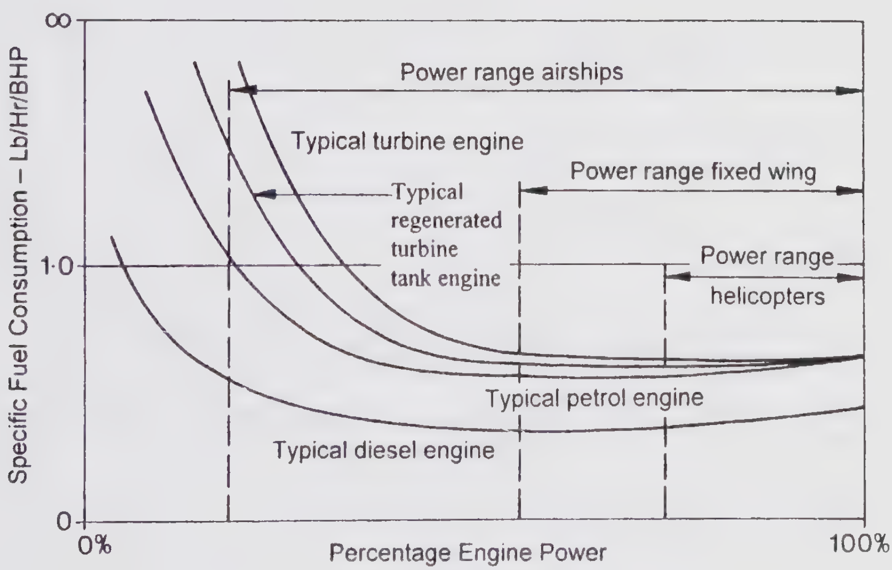


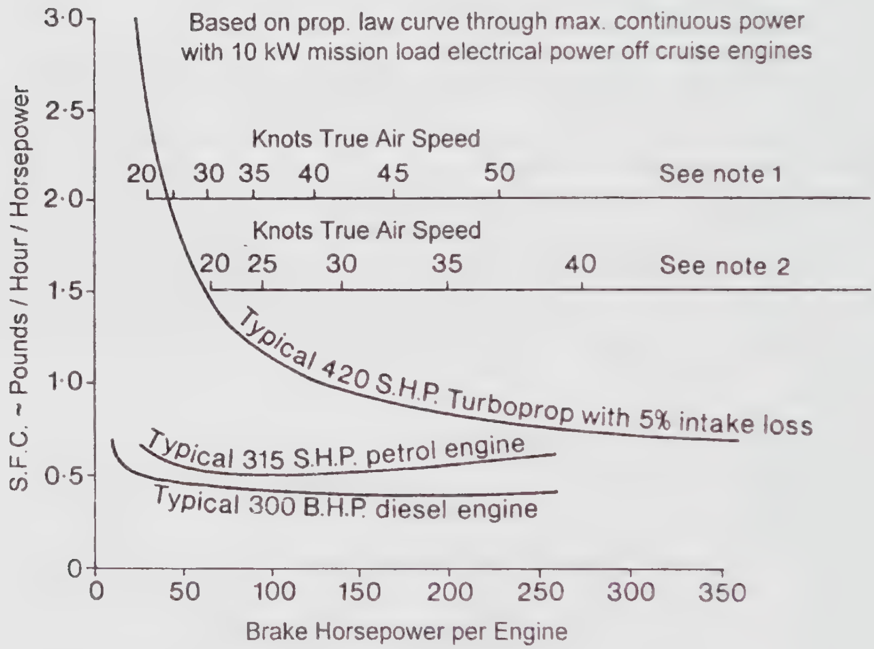
Figure 13.2. Specific fuel consumption for different aircraft types.

From this chart for these particular engines ONLY, flying at 30 KTAS, the twin engine and single engine fuel flows are:

a) Typical Turboprop: 187 & 134 Lb/Hr.

b) Typical Petrol Engine: 63 & 69 Lb/Hr.

c) Typical Diesel Engine: 53 & 51 Lb/Hr.



1. Approx. B.H.P. / engine required on a 13,000m^3 ship at 200 kg. Heavy cruising on 2 gondola mounted engines

2. Approx. B.H.P required cruising on a single engine for asymmetry

Figure 13.3. Power-SFC-Speed for turboprop and reciprocating engines in symmetric and asymmetric cruise conditions.

Airships, on the other hand, use take-off power for very short periods, typically no more than for 30 seconds, in order to obtain short field lengths and high take-off heaviness. Airships will normally cruise at much lower percentage powers.

A typical power on a small airship cruising at 30 knots could be less than 20% of TOP. Figure 13.2 shows that - at this low power - the SFCs for all engines are considerably higher, especially for turbines where they may be up to over four times that at either TOP or MCP.

The poor SFC of turbines at low power is possibly explained by their self-sustaining ground idle fuel flow. One of the most popular small turbines has a fuel flow at ground idle (zero horsepower) of 34 kg/hr/eng. (75 lb/hr/eng.). A similar sized, piston engine equipped, small airship could be cruising at in excess of 35 knots with this total ship fuel flow.

The effect of the much higher SFC of the turbine at low power can be reduced by operating on a single engine, but increased asymmetric drag must be accounted for. Piston engined aircraft may benefit in the same way. Whether a benefit is obtained, will depend on the shape of the SFC versus power curve, and the effect on propeller efficiency, for the specific engine/propeller combination. There will also be an effect caused by power offtake which is discussed later.

Figure 13.3 shows the effect of operating with one or two engines in specific cases.

The whole SFC curve for each engine that is being considered for an airship should, therefore, be obtained before the final power plant choice is made.

If the design is only intended for short duration flights, then there may be advantage in using turbines. This is because of their initial lighter installation weight compared with currently certified piston engines (it may be possible to mount them outboard and vector them if their oil system allows). However, the flight duration at which the turbine powered ship becomes less attractive than one powered by reciprocating engines, becomes lower as cruise speed increases. This is because the higher fuel flow of the turbine powered ship will cancel the advantage of the lighter installation weight of the engine above this duration. The duration at which this happens can be determined by constructing a chart similar to Figure 13.4 for the size of ship and power plants being considered. This chart should be calculated for all engines operating as well as for asymmetric cases. If no form of ballast recovery is fitted, the amount of fuel used (including reserves and ballast that may be dumped) must not, in normal use, exceed the difference between maximum heaviness and maximum lightness.

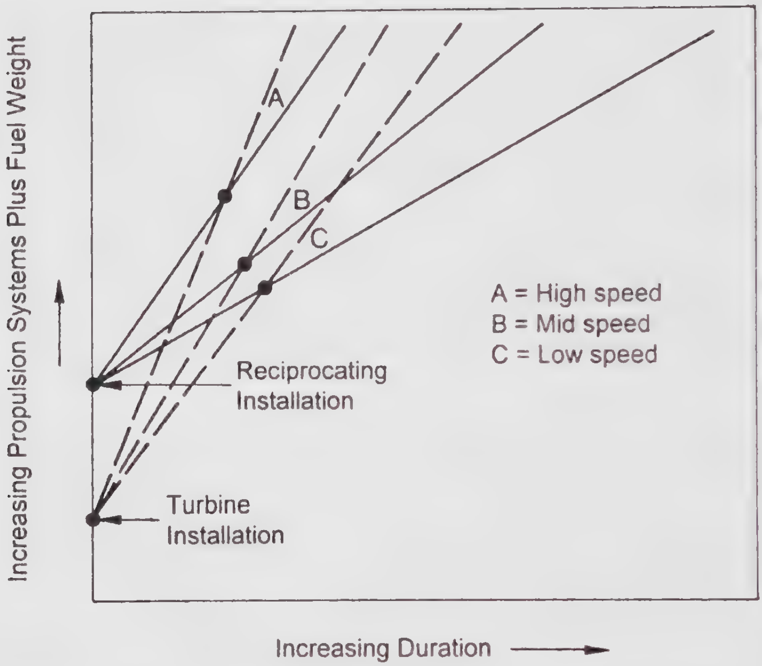


Figure 13.4. Propulsion system weight plus fuel weight against duration for two different engine types.

Calculations to obtain a chart similar to Figure 13.4 should be made for each combination of propulsion system that is being considered, taking into account maximum heaviness plus maximum lightness, if no form of ballast recovery is fitted.

POWER OFF-TAKE

Demand for electrical power to drive systems such as air conditioning in passenger airships, or missions fit for military operations, tends to be much greater now than in previous years. Because of the very low power required to propel the airship, systems consume a much higher percentage of the total power required than on HTA craft.

Compared with an HTA craft (requiring some 5 to 15% of the total engine power to drive the electronics), on some of the Military systems that have been investigated in the airship role, the electrical power required has been well over 65% of the total power required at low-medium cruise speeds. This means that the fuel used to generate the electrical power requirement may be a considerably greater driver in determining the duration of the ship than the propulsive power required as they are both included as parts of the maximum 'in flight' fuel usage.

It follows that much care must be taken in deciding how this power should be generated. Standard present day HTA craft APUs are invariably powered by small turbines with poor SFCs (by LTA standards) and are mainly producers of large quantities of air rather than the electrical power the airship requires. Piston powered APUs driving electrical generators usually require developing for the specific application, normally at very high cost. If possible, the best solution is to drive the generators from the propulsion engines which invariably give the lowest SFC (and installed weight) and hence fuel usage - but depending on the types of engines used, matching of engine/generator RPM ranges may cause problems. Also, depending on the electrical power required during the take-off phase, it may require a rework of the take-off power required.

ENGINE DRIVES AND PROPELLERS

Engines may be mounted within the gondola and connected to the propeller via gearing. This is to change direction and lower the rotational speed using shafting or belt drives etc. Alternatively, they may be directly coupled to the propellers and attached externally to either the gondola or to the envelope. In either case vectoring is an option.

Where the propellers are driven via gearing from the engines, it should be possible to obtain reasonable propeller efficiencies. These, however, are not likely to exceed 65 to 70% at normal airship cruise speeds, unless very large slow turning propellers are used. If HTA aircraft engines are used to drive propellers directly without an intermediary gearbox, then propeller efficiency is likely to be of the order of 50 to 55% in the cruise. This is because their output RPM are normally designed for the much higher HTA aircraft speeds, especially with turboprop engines. Installed efficiencies quoted in many design studies are often considerably above those that will be achieved in practice. This is because of the problem of matching propeller performance with engine output RPM and airship speed.

To obtain the highest efficiencies, a close collaboration is required between the engine, propeller and airship manufacturers from an early stage in the design process. This is because of the much lower normal cruise speeds.

SHIP WEIGHT

Chapter 9 of this book is devoted to weights. Airships are extremely frugal in the amount of fuel used for propulsion. It is worth noting that (for an airship designed to do the same job as an HTA machine) because of this frugality - depending on the speed - a unit overweight on an airship can have 200 or more times the effect on duration that it does on its HTA counterpart.

If at the design stage a weights database is not available, only data relating to ships that have been certified and in service should be used in initial construction - and then only data that are verified in their operations manuals rather than publicity material. Weight data from airships that have been built but not flown or certified must NEVER be used unless they have been personally verified. This applies even more so to weight data extracted from design studies.

Some ships that have been designed and/or built by manufacturers with no previous track record in airships have been up to 30% heavier than their design empty weight. Systems in particular, seem to be an area where over-optimism is all too frequent.

With a 30% increase in empty weight, not only all the original weight allowed for fuel disappears, but a considerable amount of the originally intended payload will have vanished, making nonsense of the originally claimed operational performance.

Weight estimation and control is of far greater importance in airship design than in that of HTA aircraft.

GAS LIFT

Gas lift for a particular volume envelope, without superheat, depends mainly upon the pressure height and the temperature conditions for which the envelope is filled. This affects the percentage fill relative to I.S.A. sea level conditions. The purity of the helium also alters the lift. Initially the cruise height, helium purity and temperature conditions for the design case have to be established.

To allow for variations in temperature, superheat and atmospheric pressure, a pressure height of 1,000 feet above the required cruise height is usually selected. This ensures that the cruise height requirement is met for much or most of the time.

Modern envelope materials with their superior ability to maintain the purity of helium, allow the use of higher percentage helium purities for the design case than were used in the past. A purity of 97.5% now seems acceptable.

Table 13.1 gives the gas lift per 1000 m^3 volume with varying pressure height, temperature and 97.5% helium purity. Values may be factored for other purities.

Table 13.1. *Gas lift per 1,000m³ envelope volume*

Temperature	ISA-20°C	ISA-10°C	ISA	ISA+10°C	ISA+20°C	ISA+30°C	ISA+40°C
Pressure Height (Feet)	**GAS LIFT (kg per 1,000m³ envelope volume)**						
0	1,107	1,067	1,030	995	963	933	904
1,000	1,075	1,036	1,000	966	935	905	877
2,000	1,044	1,006	971	938	907	878	851
3,000	1,014	977	942	910	880	852	825
4,000	985	948	915	883	854	826	800
5,000	956	921	887	857	828	801	776
6,000	928	893	861	831	803	777	752
7,000	901	867	835	806	778	753	729
8,000	874	840	810	781	754	729	706
9,000	848	815	785	757	731	706	684
10,000	822	790	761	733	708	684	662
15,000	702	674	648	624	602	581	561
20,000	597	572	549	528	508	490	473
25,000	504	482	461	443	426	410	395

For design purposes, when a fill has been made for a particular pressure height and temperature condition, gas lift remains constant (except for changes to helium purity and superheat) up to pressure height irrespective of the temperature or altitude at which the ship flies.

The effect of lowering temperature is to increase the pressure height and, vice versa, increased temperature lowers it.

Superheat on the ground does increase lift by replacing some of the heavier air by an identical volume of lighter helium in the envelope. This may not be of use insofar as, after the superheat has worn off in flight, the ship must not exceed the maximum heaviness. if all the superheat does not wear off in flight, then pressure height reduces. In design, no superheat should be assumed as it may not exist.

Over water throughout the world, at distances more than about 50 n.m. offshore, the temperatures seldom exceed I.S.A.+13°C and the diurnal temperature variation is quite small. In such locations, using the I.S.A. gas lift can probably be accepted for most of the time. This is true providing a pressure height of 1,000 feet above the required cruise height is used.

Over land, especially in mountainous desert areas, temperatures may exceed I.S.A.+30°C during the day with a very high diurnal temperature range. In such locations, accurate temperatures should be used. (At sea level and up to 9,000 feet pressure altitude flight - with a possible 40°C diurnal temperature range - requires 34 % volume ballonets with a take-off at the coldest part of the day to obtain best take-off performance).

It should be remembered that, in calculating gas lift, we are dealing with a volume that is normally retained by a flexible cloth, which is harder to control dimensionally than rigid materials. Linear tolerances are unlikely to be controlled to a greater accuracy than ± 2% which will give a theoretical volumetric spread of ± 6.12%. In practice, because of the construction of the material, the volumetric tolerance does not usually exceed ± 2%. Therefore, in order to be able to meet any guarantees for lift based on the negative side of the nominal dimensions, linear dimensions for manufacture will have to be for a volume 2% higher than that calculated.

AIRSHIP SIZING

A method of determining the size of airship required, is to crossplot the airship volume against weight available for fuel, and overlay on the same chart the fuel weight required for the particular mission. Figure 13.5 shows a hypothetical cross plot.

For the first estimation, only three points will provide sufficient accuracy. For different hull volumes, the gas lift should be calculated and from this the weight of the ship subtracted including mission equipment, furnishings, crew, food and any other items intended for carrying on the ship. This will give the amount of fuel that can be carried at each volume. Normally, heaviness will equal the water and other disposable ballast agreed with the licensing authorities. In some cases, these authorities allow fuel to be considered as dumpable ballast. In this case, the amount of fuel - up to maximum heaviness - minus any other dumpable ballast (such as disposable nose ballast) can be added to the above amount of fuel. If fuel is permitted as dumpable ballast (in requirements that have been published world-wide up to now) the maximum heaviness at take-off must not exceed the lesser of the structural maximum heaviness, or 80% of fuel on-board at take-off plus any other disposable ballast.

For each volume, the fuel required for the design mission requirement can be calculated from the drag, propeller efficiency and engine power SFC curves.

It is desirable that the final calculation of ship volume is not made until the weight estimates for the car, propulsion system, fins, landing gear and other systems are largely determined. Unfortunately, the envelope is such a highly visible and relatively low cost item, that pursuance of funding often determines that it is made first.

By adding percentage discrepancies in estimating ship weight, to the ship weights estimated for Figure 13.5, revised volumes for these discrepancies can be determined.

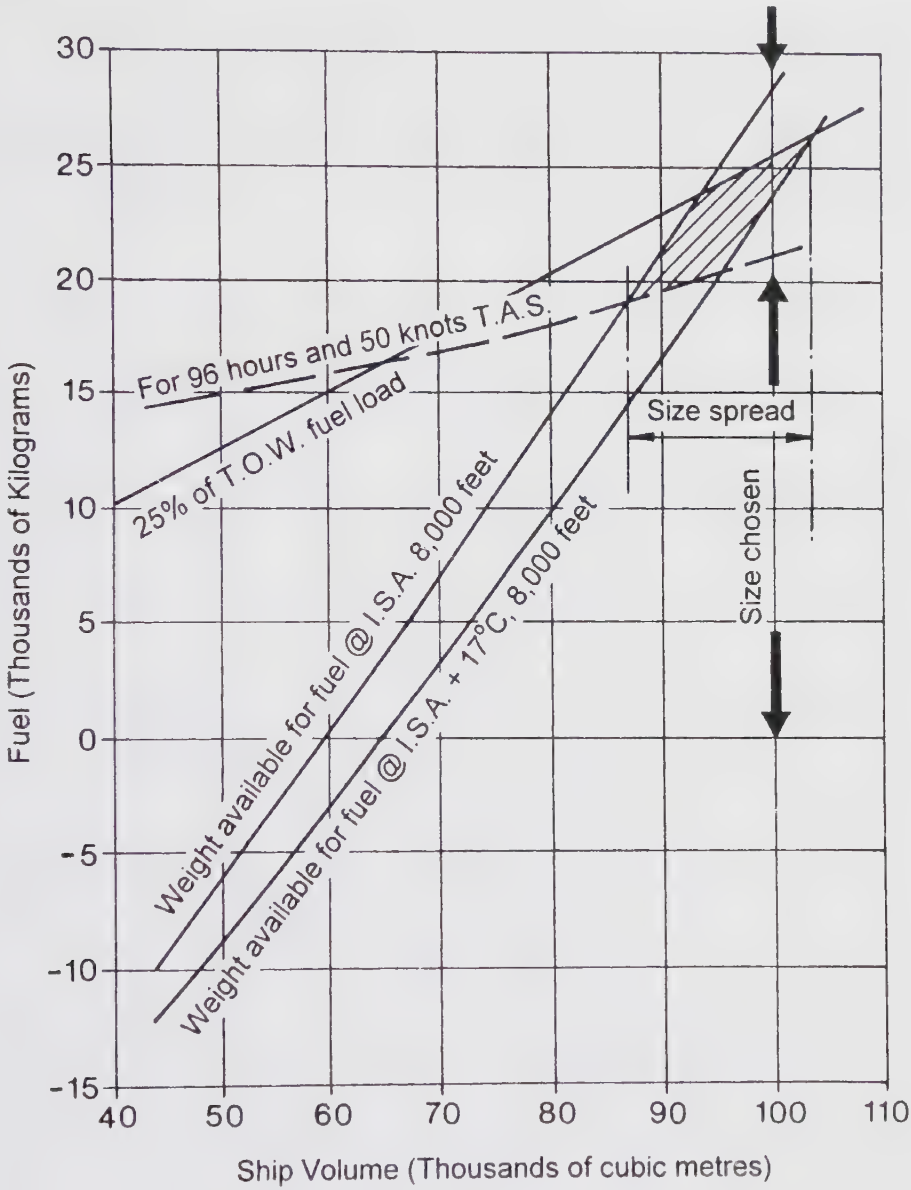


Figure 13.5. Initial ship sizing chart.

EFFECT OF WIND

When operating in their ideal roles of patrol and surveillance, or in advertising and tourism, airships are only marginally affected by wind. This is because of their normally racetrack pattern over the ground, and their ability to 'fly the isobars' if necessary,

If, however, the ship is required to make a passage, then wind has a large effect on its performance. This is because of airships' relatively low airspeed,.

An example of the effect on range of flying into a headwind is shown on Figure 13.6 for a particular airship of approximately 90,000m^3 volume. A similar chart should be constructed for any ship where passage making is to be made. Note that water recovery was used in this study.

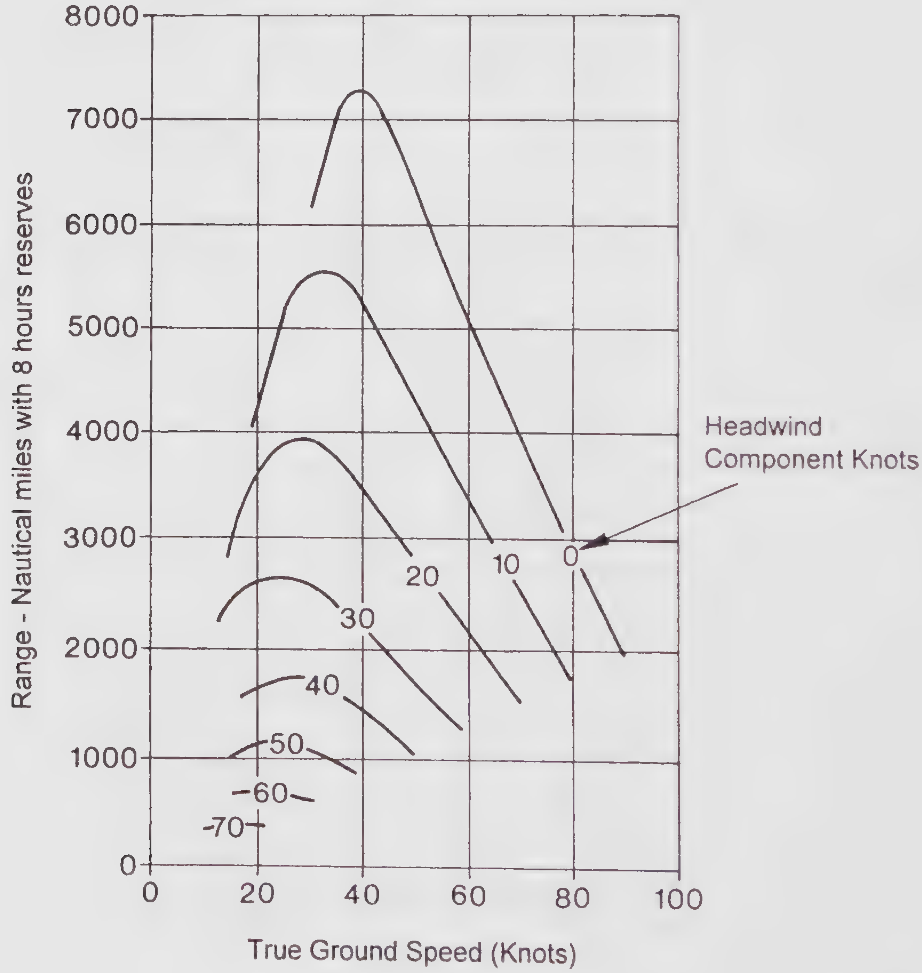


Figure 13.6. Range against true ground speed for different headwinds.

The cruise speed, in knots of true airspeed, in the graph is obtained by adding the true groundspeed to the headwind component at the range.

According to the U.S. Weather Bureau Technical Paper no. 41 'Upper winds over the northern hemisphere' dated June 1961, the average scalar wind (50 percentile) over London at 5,000 feet is over 26 knots during December to February and 19 knots during June to August. A scalar wind is one that can come from any direction. The 90 percentile scalar winds for the same periods were 48 and 33 knots respectively. An airline would normally timetable route timings using the 90 percentile headwinds for the actual route they were flying.

Airships, however, could not have their route and timings planned in this way. On passage making, they would operate far more like a clipper ship taking best advantage of whatever winds are met.

14

Improvements

E. Mowforth

INTRODUCTION

Many of the airship's principal operational problems are associated with the functions of buoyancy control, of fuel consumption and of interface movements - i.e. landing, mooring, load exchange and take-off.

Certain modifications to the basic airship concept have been introduced in recent years which help to some extent in the above areas. An obvious example is vectored thrust, originally used on a number of airships prior to 1920 and on the US Navy's 'Akron' (1931-33) and 'Macon' (1933-35), and then re-introduced for the Airship Industries Skyship series in the 1970s. Control effectiveness has also been improved, with reduced pilot effort, in experimental ships using fly-by-wire or fly-by-light transmissions in place of direct tension cables.

The US Navy's rigid airships of the 1930s also used exhaust water recovery, with some success, to reduce in-flight weight loss owing to fuel consumption, and this technique has also been proposed for modern diesel-powered projects, although such an installation does not yet appear to have flown.

In addition to these proven expedients, many other theoretical approaches to buoyancy, fuel consumption and interface problems are constantly being proposed. Many of these are impractical, usually because of the weight penalty involved. Other proposals may have a marginal applicability in particular cases. Such proposals are made repeatedly by different agencies. This chapter sets out to survey briefly, and to evaluate, some of the more common of these concepts.

BUOYANCY CONTROL BY LIFTING GAS MANIPULATION

The concept of in-flight buoyancy control of pressure airships through lifting gas manipulation is often put forward. The commonly suggested forms of such a technique are discussed in this section.

Lifting Gas Pressurisation

The intention here is to increase the input pressure to the ballonets and hence to the lifting gas. Lift will then be reversibly reduced through both the decrease in lifting gas volume and the increase in its density, and also to some extent through the raised density of the air in the ballonets.

Figure 14.1 compares two conditions of a pressure airship`s envelope-ballonet combination

In Figure 14.1(a) the ballonet and gas mean pressures are assumed to be atmospheric (p_a), neglecting the aerostatic gradient. For a maximum envelope volume V_o and an inflation fraction I_o the static lift is then:

$$L_o = I_o V_o(\rho_a - \rho_g) \tag{14.1}$$

where ρ_a and ρ_g are the densities at atmospheric pressure of air and gas respectively.

In Figure 14.1(b) the ballonet, and hence the envelope, have been pressurised to a higher value p_g, assuming isothermal processes throughout; this raises the gas density to $(p_g/p_a)\rho_g$ and decreases the gas volume to $(p_a/p_g)I_oV_o$. At the same time the ballonet increases in volume to $[1-(p_a/p_g)I_o]V_o$ and air density inside becomes $(p_g/p_a)\rho_a$.

The total lift of the pressurised system is then:

$$L_p = (p_a/p_g)I_oV_o[\rho_a -(p_g/p_a)\rho_g] - [1-(p_a/p_g)I_o]V_o[\rho_a(p_g/p_a -1)] \tag{14.2}$$

where the second term represents the additional weight of air in the ballonet.

The proportional reduction in lift owing to pressurisation is therefore $(L_o - L_p)/L_o$, which reduces to:

$$\delta L/L_o = (\delta_p/p_a)/\{I_o[1-(\rho_g/\rho_a)]\} \tag{14.3}$$

where δL is the lift reduction owing to a pressure differential of δp (= $p_g - p_a$).

It will be more convenient to express this lift reduction as a proportion of the 'zero pressure' disposable lift, taken as $L_{do} = k_d.L_o$:

$$\delta L/L_{do} = (\delta_p/p_a)/\{k_dI_o[1- (\rho_g/\rho_a)]\} \tag{14.4}$$

Account must now be taken of the reduction in disposable lift arising from the increased envelope weight necessary to contain the higher gas pressure.

The envelope weight may be taken to comprise a fixed component, independent of pressure differential, owing to various attachments, proofing and protective layers and reinforcements, and a basic skin component representing the tensile skin containing the internal pressure. The latter component, W_s, may be assumed proportional to the differential pressure across the skin, i.e. $W_s/L_o = k_s.(\delta_p/p_a)$. If pressurisation is contemplated the skin weight will have to be adequate for the intended differential, even when the latter is not applied, so that the maximum available (zero pressure) disposable lift will become:

$$L_d \quad = \quad L_{do} - W_s \quad \text{or} \quad L_d/L_{do} \quad = \quad 1 - (k_s/k_d)(\delta_p/p_a) \qquad (14.5)$$

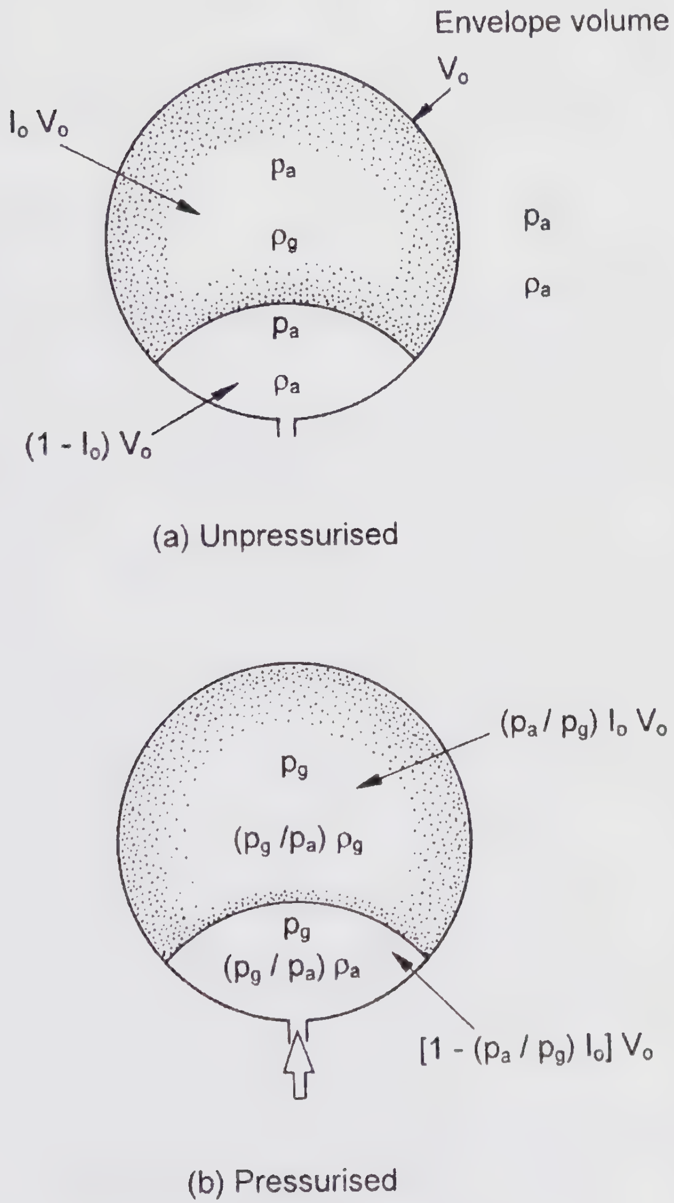


Figure 14.1. Mechanism of Lifting Gas Pressurisation.

To choose some typical values, (ISA Sea Level):

I_o	=	0.9
ρ_g	=	0.170 kg/m^3 (helium)
ρ_a	=	1.226 kg/m^3
k_d	=	0.4
k_s	=	10

Equation 14.4 then gives:

$$\delta L/L_{do} = 3.225(\delta_p/p_a) \tag{14.6}$$

and Equation 14.5 gives:

$$L_d/L_{do} = 1 - 25(\delta_p/p_a) \tag{14.7}$$

Equations 14.6 and 14.7 are plotted in Figure 14.2, from which it is clear that the weight penalty introduced by the necessity for increased envelope strength prohibits the generation of any significant degree of buoyancy control through gas pressurisation.

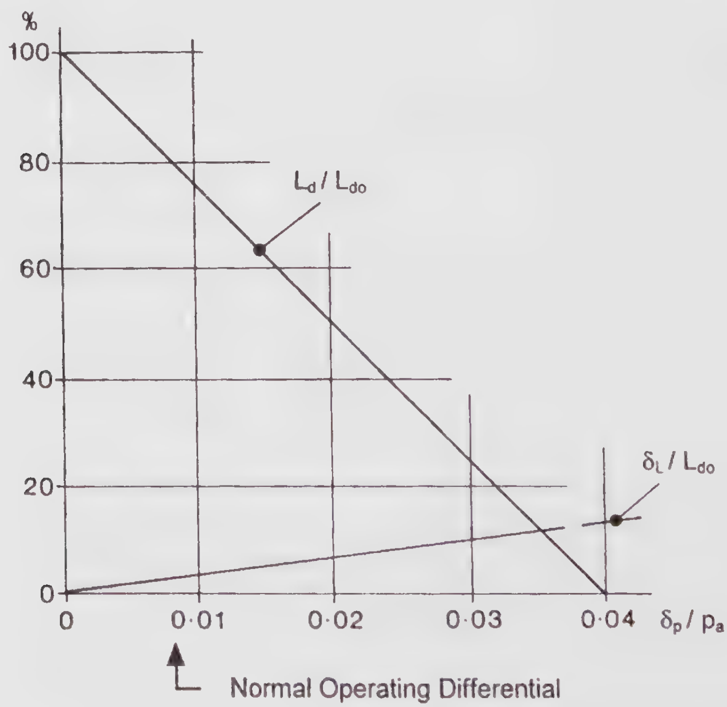


Figure 14.2. Effects of Lifting Gas Pressurisation.

The value of 0.4 was chosen for k_d to bring the disposable lift down to a typical value of $0.3L_o$ with a representative operating differential of about 0.01 atmospheres. Any further increase of differential causes a drastic erosion of the disposable lift, which disappears altogether if the envelope is designed for a differential of 0.04 atmospheres.

The above figures are of course dependent upon the values assumed for the constants in the equations, but no reasonable deviations from these values can confer viability upon the proposed system.

Lifting Gas Heating

In this proposed system the lifting gas does not generate sufficient lift for operational flight when at ambient temperature. Before flight, therefore, the gas is heated to increase lift to the desired level, and buoyancy may then be controlled by further heating or cooling.

For application of this mechanism in a pressure airship it is usually suggested that heating be applied via the air in the ballonets, for example by using engine exhaust gases. Figure 14.3 shows the parameters of such a system, in which the lifting gas and the ballonet air are assumed to be at the same temperature both when 'cold' (Figure 14.3(a)) and when heated for lift augmentation (Figure 14.3(b)): in all cases T represents Absolute Temperature, and all changes take place under constant pressure.

In Figure 14.3(a) the temperatures throughout are absolute (°K) and atmospheric (T_a), and the corresponding air and gas densities are ρ_a and ρ_g. The static lift is then given by Equation 14.1, as before. I_{oc} is the inflation fraction when 'cold' at sea level.

A rise in ballonet and gas absolute temperature to T_g increases the inflation fraction to $(T_g/T_a)I_{oc}$ and reduces the gas and ballonet air densities in the same ratio, so that the total lift becomes, by reference to Figure 14.3(b):

$$L_t = (T_g/T_a)I_{oc}V_o[\rho_a - (T_a/T_g)\rho_g] + [1-(T_g/T_a)I_{oc}]V_o\rho_a[1-(T_a/T_g)] \qquad (14.8)$$

where the second term represents the lift owing to the ballonet.

The proportional increase in lift then becomes $(L_t - L_o)L_o$, which reduces to:

$$\delta L/L_o = [1-(T_a/T_g)]/\{I_{oc}[1-(\rho_g/\rho_a)]\} \qquad (14.9)$$

or, in terms of a 'cold' payload $L_{do} = k_d \, . \, L_o$,

$$\delta L/L_{do} = \delta T/\{k_d I_{oc}(T_a+\delta T)[1-(\rho_g/\rho_a)]\} \qquad (14.10)$$

where δT is the temperature difference (T_g-T_a).

Assuming typical values (ISA Sea Level):

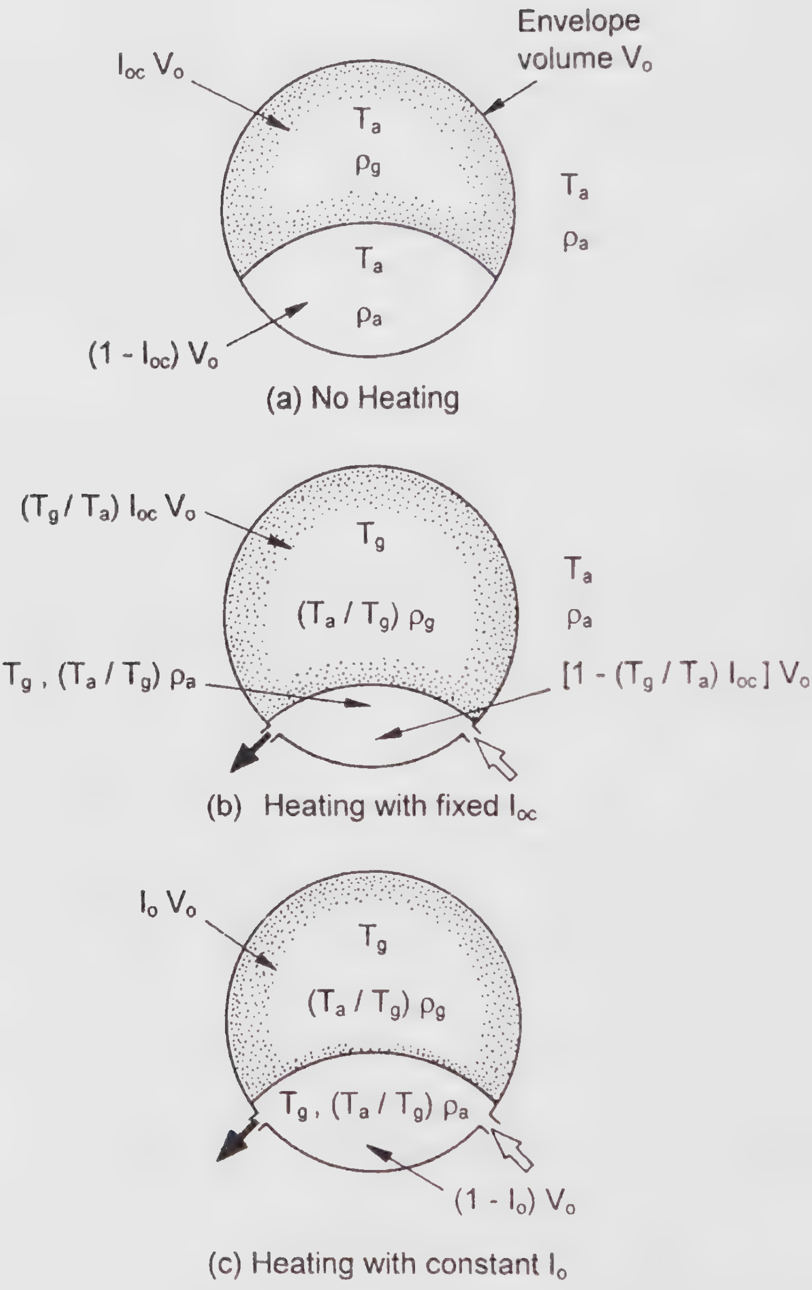


Figure 14.3. Mechanism of Lifting Gas Heating.

I_{oc}	=	0.9
ρ_g	=	0.170 kg/m^3 (helium)
ρ_a	=	1.226 kg/m^3
k_d	=	0.3 (referred to datum δ_p of 0.01 atmospheres)
T_a	=	288°K

Equation 14.10 reduces to:

$$\delta L/L_{do} = 4.3/[1+(288/\delta T)] \tag{14.11}$$

This result, plotted in Figure 14.4, appears to imply a dramatic increase in payload for a relatively small rise in temperature. Unfortunately the same rise in temperature reduces the pressure height: the ballonet volume is $(1-(T_g/T_a)I_o)V_o$, and if I_{oc} is 0.9 this volume becomes zero - i.e. the pressure height falls to sea level - when $T_g = T_a/0.9 =$ 320°K, representing a temperature differential δT of only 32°C.

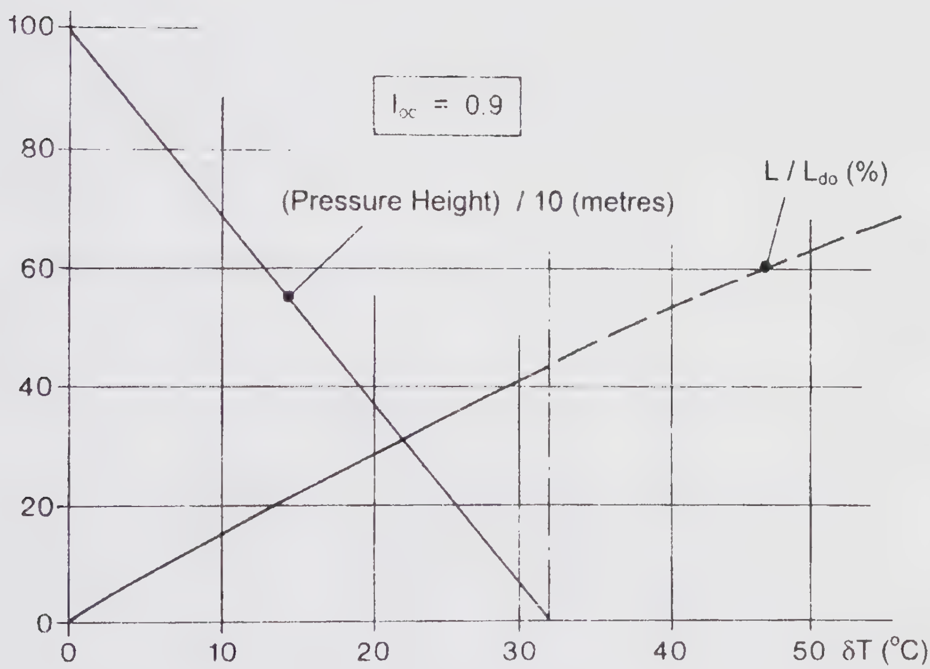


Figure 14.4. Effects of Gas Heating with Fixed I_{oc}.

For operational purposes it is necessary to maintain a fixed pressure height, which means that at sea level the 'hot' inflation fraction must remain the same for any working temperature. If this fraction is to be I_o, then the corresponding 'cold' value will have to be $I_{oc} = (T_a/T_g)I_o$, so that heating from T_a to T_g will bring I up to I_o. This represents a proportional saving in lifting gas of $[1-(T_a/T_g)]$, which may or may not become significant.

For a fixed I_o, the lift gain through heating becomes (referring to Figure 14.3(c)):

$$L_t = I_o V_o[\rho_a - (T_a/T_g)\rho_g] + (1 - I_o)V_o\rho_a[1 - (T_a/T_g] \tag{14.12}$$

and this reduces to a proportional lift increase, referred to the 'cold' disposable lift L_{do} at $I_{oc} = I_o$, of:

$$\delta L/ L_{do} = (1/ k_d)[1-(T_a /T_g)]\{1/[I_o(1-(\rho_g/\rho_a))]-1\} \tag{14.13}$$

Inserting the values already used, this becomes:

$$\delta L/L_d = 0.97/[1+(288/\delta T)] \tag{14.14}$$

This is only 22.5% of the gain from a fixed I_{oc} represented by Equation 14.11, but it offers a fixed pressure height of about 1000 m (3300 ft) and a helium saving of $100/[1+(288/\delta T)]$%. Values from Equation 14.14 are plotted in Figure 14.5, where it is seen, for example, that a working temperature differential of 25°C will increase the disposable lift by about 8% and save about the same proportion of helium.

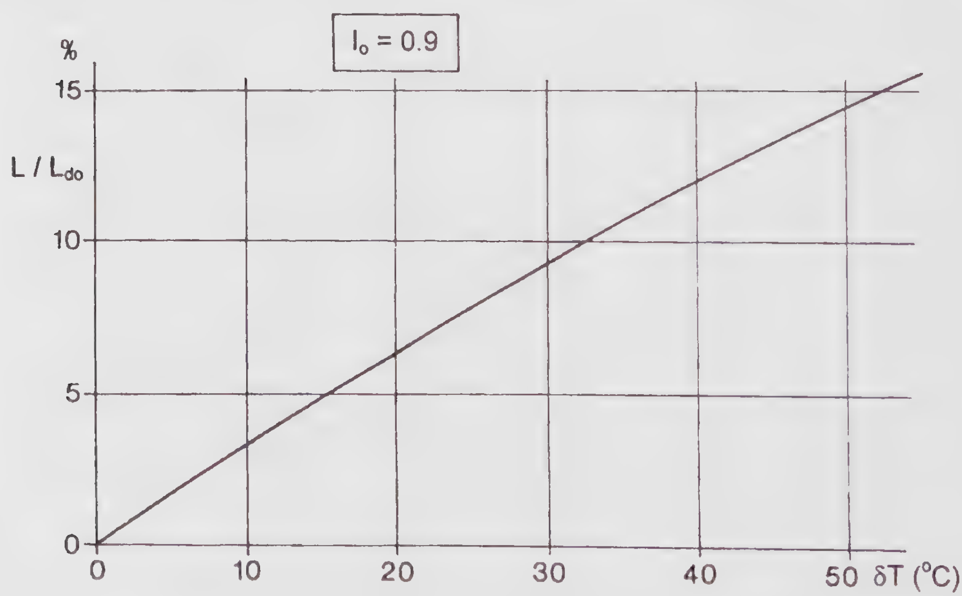


Figure 14.5. Effects of Gas Heating with Fixed I_o.

The question of whether such gains are worthwhile in a real situation must depend upon the penalties in time, weight and energy incurred in heating. Turn-round time may be seriously affected if the gas is allowed to cool on landing and must then be reheated for take-off: the alternative of maintaining the differential throughout the ground handling sequence may involve a considerable expenditure of energy.

The installation weight could be small if it is practicable - as usually proposed - to heat the system by simply diverting exhaust gas into the ballonets. This raises the question of how much heat would be required, and only a very approximate estimate of this can be offered here because the static heat transfer characteristics of skin materials may be subject to wide variation and in-flight values will also increase with airspeed.

For a superheat δT, the heat loss through the skin will be:

$$H = k_s S \delta T = k_s (N Q^{2/3}) \delta T \tag{14.15}$$

where: k_s is the skin heat transfer coefficient.

S is the envelope skin area $= N.Q^{2/3}$ (Q = envelope volume)

It is convenient to relate this heat flow to the propulsive power P, given approximately by:

$$P = \rho_a Q^{2/3} V^3/K_p \tag{14.16}$$

where V is the airspeed and K_p is an overall Coefficient of Performance for the airship.

From Equations 14.15 and 14.16:

$$H/P = \{[k_s N K_p]/\rho_a V^3)\} \delta T \tag{14.17}$$

Assuming:

k_s = $2 W/m^2/°C$.

N = 8 (for a typical modern profile).

K_p = 55 (based on statistics for existing medium-sized airships).

Equation 14.16 gives:

$$H/P = 700\delta T/ V^3 \text{ approximately} \tag{14.18}$$

For an airship cruising at 100 km/h (62.5 mph), Equation 14.18 suggests that the heat flow required to maintain a temperature difference of 25°C would be about 80% of the propulsive power - which, for a piston engine of typical efficiency, would also be about 80% of the heat in the exhaust flow.

It is extremely unlikely that even half of this heat could be extracted from the exhaust gases without the weight and cost penalties of a sophisticated heat exchange system: the ballonet air would have to be heated through at least twice the superheat temperature of the lifting gas to secure the necessary heat flow through the relatively small ballonet skin area, and the effectiveness of simple through-flow heating would be reduced as the ballonet volume diminished with altitude. Exhaust heat would also become even more inadequate at lower airspeeds.

A possible remedy would be a double-skinned envelope to reduce the heat transfer coefficient, but this would raise the skin weight by at least 50%, and the resulting disposable lift loss of about 15% would immediately cancel any lift gain due to heating. The above analysis is highly approximate, but it does not seem probable that practicability could be conferred upon a gas heating system by any reasonable range of adjustment of the assumed figures.

A more optimistic estimate of the waste heat available from the propulsion system was offered in a Goodyear survey of 1975. This assumed direct heating of the gas through a heat exchanger installation of 60% efficiency, apparently drawing upon heat from the engine cooling system as well as from the exhaust; this would represent a considerable installation weight. The pressure height factor was not mentioned.

Compressed Air Storage

Whilst it would not be realistic to attempt storage of a sufficient weight of compressed air to balance the whole payload, there may be some advantage in progressively storing air under pressure to balance the weight of fuel consumed, or to make a moderate range of buoyancy control available for dealing with superheat or the effects of rain and ice.

The practicability of such a system would be conditioned by the power expended in compressing the air, and the weight and volume of the storage facility. To assess these parameters it will be assumed that air is being stored in a container of volume Q_c at a mass flow rate m_a, which is low enough to allow effectively isothermal compression. ISA sea level ambient conditions are assumed for simplicity, represented by atmospheric pressure p_a and absolute temperature T_a. The universal gas constant for air is R_a, so that the mass of air in the container before delivery starts will be:

$$M_{ao} = (p_a Q_c)/(R_a T_a) \qquad (14.19)$$

After a time t the mass of air in the container will be $m_a t+M_{ao}$ and under isothermal conditions the pressure ratio is then:

$$R_p = 1+(m_a t/M_{ao}) \qquad (14.20)$$

The work done in compressing air to this condition is:

$$U = p_a Q_c(R_p-1)\ln R_p \qquad (14.21)$$

and the power at time t is $P_t = dU/dt$, or:

$$P_t = (p_a Q_c m_a / M_{ao})[1 - 1/R_p + \ln R_p] \tag{14.22}$$

If it is assumed that air storage will be in long cylindrical tubes, it can be shown that to hold enough air for a flight time T the minimum weight of such tubing, irrespective of its dimensions or pressure ratio, will be approximately:

$$W_c = 2 m_a T R_a T_a (\rho_c / \sigma_{max}) \tag{14.23}$$

where ρ_c and σ_{max} are respectively the density and design tensile stress for the container material.

By way of illustration the above parameters will be evaluated, as functions of the storage pressure ratio R_p, for a hypothetical airship of envelope volume 50,000 m^3 (1.75 m ft^3) cruising at about 80 mph (36 m/sec) for a flight time T of 10 hours. ISA sea level conditions are assumed throughout, giving $\rho_a = 10^5$ N/m^2, $R_a = 287$ J/kg°K and $T_a = 288$°K.

The propulsive power required for the airship will be, from Equation 14.16, about 1,500 kW (2,000 hp).

Assuming an average fuel consumption rate of 10^{-4} kg/kW-s (0.5 lb/bhp-h), m_a to compensate this flow will then be $1{,}500 \times 10^{-4} = 0.15$ kg/s (0.33 lb/s). In 10 hours the total fuel flow $m_a T$ will then be ($0.15 \times 10 \times 3{,}600$) = 5,400 kg (5.4 tonne). Then from (20), $M_{ao} = 5400/(R_p - 1)$, and from Equation 14.19, $Q_c = 4{,}463/(R_p - 1)$ m^3.

The power required to compress the air will increase as the pressure rises, and will be a maximum when the final ratio R_p is reached. From Equation 14.22, the final power in this case will be:

$$P_T = 12.4(1 - 1/R_p + \ln R_p) \text{ kW} \tag{14.24}$$

Values of peak power from Equation 14.24 are given in Table 14.1.

Table 14.1. *Peak power required to compress air*

R_p	2	4	6	8	10
P_T (kW)	14.8	26.5	32.6	36.6	39.7
P_T (hp)	19.7	35.3	43.5	48.8	52.9

Assuming storage to be in tubing of filament-wound fibreglass, of working tensile strength $3x10^8 N/m^2$ and density 1800 kg/m^3, Equation 14.23 gives the bare weight of tubing as 5,356 kg (5.356 tonne). In practice, ducting, valves, mountings and a separate compressor unit would raise this to at least 6 tonne, or about 30-40% of the disposable lift. It is unlikely that the container weight could be reduced with commercially available materials, although it might be possible to reduce the weight of compressor plant by tapping air directly from supercharger delivery in a piston engine, or from compressor delivery in a gas turbine unit.

The storage volume Q_c (= $4{,}463/(R_p\text{-}1)\ m^3$) would also be very high (Table 14.2).

Table 14.2. *Storage volume of compressed air*

R_p	2	4	6	8	10
$Q_c\,(m^3)$	2,232	1,116	719	558	446
$Q_c\,(ft^3)$	78,120	39,060	25,165	19,530	15,610

For example, the volume for R_p = 8 would represent over 700m (2,300 ft) of 1m (3.3 ft) diameter tubing.

The power required for compression is minimal - never likely to exceed 3% of the propulsive power - but the container weight and volume to carry the stored air would appear to make this system impracticable as a means of fuel loss compensation for any realistic flight time.

Equation 14.23 shows that the container weight is proportional to the weight of air stored, so a control range of, say, 1 tonne, would require a storage weight of about 1-1.5 tonne: this control range would, however, be only about 2% of gross lift and would therefore only be of limited benefit.

Compressed Storage of Lifting Gas

If a mass m_g of lifting gas is removed from the envelope, the lift loss is $(m_g/\rho_g)(\rho_a\text{-}\rho_g) = m_g[(\rho_a/\rho_g)\text{-}1]$: if the extracted gas is stored in an on-board container the mass of the container will increase by m_g, so that the total lift loss is the sum of the two elements, i.e. $(\rho_a/\rho_g)\, m_g$.

Assuming, as with the preceding compressed air analysis, that a lift loss rate equivalent to a fuel consumption rate m_f is required:

$$m_g \;=\; (\rho_g/\rho_a)\, m_f \tag{14.25}$$

Proceeding immediately to the container weight, which proved to be a critical factor in the preceding case, analogy with Equation 14.23 gives:

$$W_c = 2(\rho_g/\rho_a)m_fTR_gT_a(\rho_c/\sigma_{max}) \qquad (14.26)$$

Using values already quoted for a 10-hour flight, with R_g for helium = 2,080 J/kg°K, Equation 14.26 gives a minimum container weight of 5,380 kg (5.38 tonne) - close to the container weight of 5,356 kg for the compressed air system - and the volume required will also be about the same. The helium storage system therefore seems to suffer the same principal disadvantages as the compressed air proposal. In addition, the helium system would in all cases require a separate compressor facility, and possibly a heat source to avoid cooling of the lifting gas when helium is returned to the envelope from compressed storage.

Liquefied Helium Storage

It is not possible to quantify a liquid helium storage system even as approximately as in the preceding estimates: storage of liquefied helium for release to augment lift as required has been seriously proposed, but the more useful technique of liquefying helium in flight to reduce lift does not appear to have been studied.

It seems improbable that a light enough liquefaction installation could be designed for any reasonable size of airship, particularly as the liquefaction process would be complicated by the inevitable air contamination of gas withdrawn from the envelope.

The reverse process of releasing helium into the envelope is more plausible, but would require a heating facility for bringing the gas up to ambient temperature to stabilise the static buoyancy.

BOUNDARY LAYER CONTROL

For a typical airship in steady axial flight, part of the total aerodynamic drag owes its origin to the bare hull and the remainder is generated by fins, engines and the control car. The latter appendages produce drag not only because of their own resistance but also through their interference with the flow over the main hull. Because of this interaction it is not easy to separate quantitatively the contributions of the different elements to the overall drag; collected data suggest that the 'bare hull' drag accounts for about 60-70% of the total, the proportion increasing with airship size as the appendages become smaller in relation to the hull. It is therefore worthwhile considering any process that might significantly reduce this bare hull component.

The bare hull drag is primarily conditioned by the behaviour of the boundary layer, and could in theory be considerably reduced by inhibiting the growth of the boundary layer along the outer skin. A simplified model illustrating the mechanism of hull drag generation is shown in Figure 14.6.

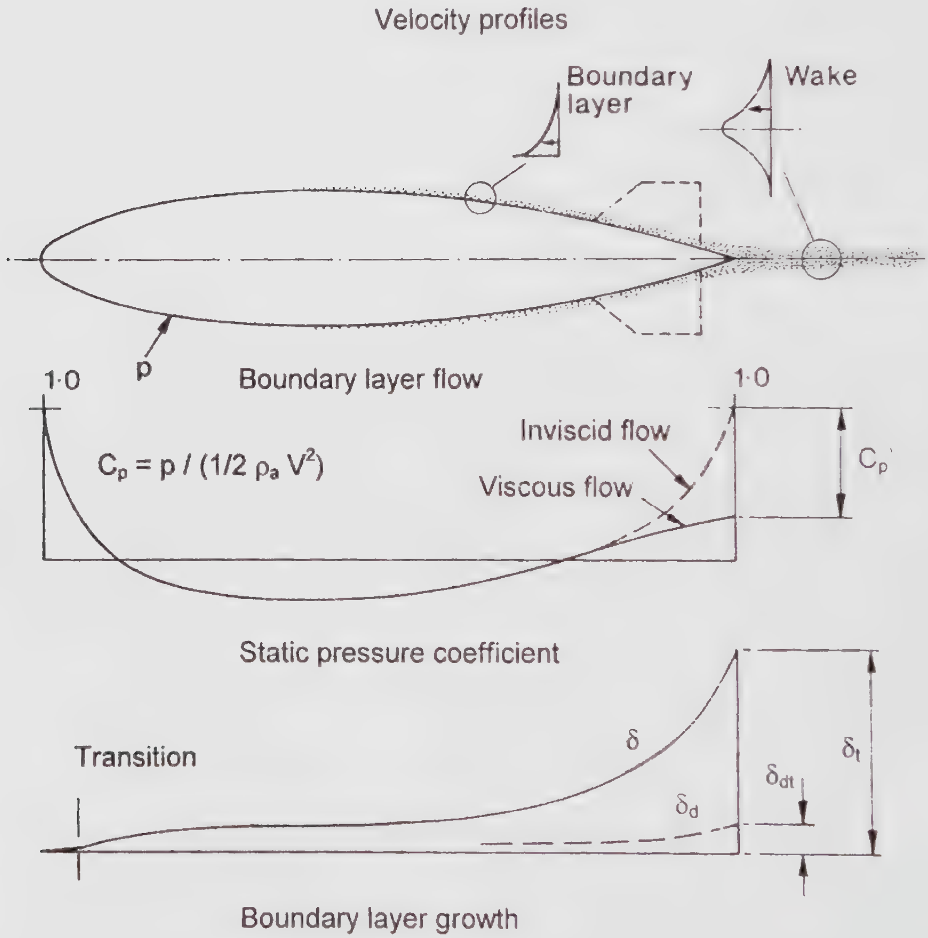


Figure 14.6. Aerodynamic Drag of an Airship Hull.

On a full-sized hull in axial flight the transition from laminar to turbulent flow in the boundary layer takes place very near the nose, and the turbulent layer then grows in thickness along the hull. The rate of growth is conditioned by the local value of the static pressure p normal to the hull surface, plotted in Figure 14.6 in terms of the static pressure coefficient C_P $\{= p/(1/2\rho_a V^2)\}$. This pressure falls with distance from the nose to a minimum at about 40% of the length, and then begins to rise again. The boundary layer thickness δ grows more rapidly in an adverse pressure gradient, so towards the tail the rate of growth increases sharply because of both the adverse gradient and the decreasing hull circumference; the boundary layer finally leaves in the form of an axisymmetrical wake. The axial flow in this wake follows the hull at a speed less than that of the airship, so that energy must be continuously fed into the wake to sustain its forward momentum, and the drag generated by this energy drain is usually represented as the 'surface friction drag', since it is the frictional force along the hull skin that originally induces the forward flow in the boundary layer and wake.

The presence of a thick boundary layer towards the tail also has a reciprocal effect on the static pressure distribution in this area: the aerodynamic profile of the hull is effectively enlarged, so that the pressure recovery is less than for the ideal case of inviscid flow, and the forward thrust owing to tailcone pressure is reduced. This effect appears as an additional drag term, called 'form drag': in an ideal inviscid flow regime with no boundary layer the pressure recovery would be such as to eliminate this drag altogether.

The true thickness δ of a boundary layer cannot be exactly defined because of the asymptotic nature of its internal velocity profile, but is typically taken as the thickness within which the flow velocity relative to the airship skin increases to 99% of the free stream value. Another useful parameter is the 'displacement thickness' δ_d, defined as the radial distance through which the hull profile is apparently displaced outwards by the flow in the layer to generate a new 'ideal flow' profile, shown in Figure 14.7. This is the 'hard' profile that would generate the same distribution of static pressure in a hypothetical inviscid flow field as does the real profile in its actual viscous flow regime. It can be shown that δ_d is also the thickness that would pass the same flow as the true boundary layer if the flow velocity within it were the same throughout as the free stream velocity.

For purposes of illustration the systems described may be roughly simplified to the model shown in Figure 14.7, where at the extreme tail the equivalent hull profile is cut off with a radius equal to the local displacement thickness δ_{dt}, the wake radius is taken to be the same as the boundary layer thickness δ_t, the airship forward speed is V, and the flow within the wake area ($= \pi\, \delta_t^2$) is assumed to have a uniform value: v_w. d_t and d_{dt} are defined in Figure 14.6 as the values of boundary layer and displacement thickness respectively at the extreme tail.

The form drag is then taken as the force due to a pressure deficit p' acting on the projected transverse area $\pi\, \delta_{dt}^2$, where $p' = \beta\rho_a V^2\, C_p'/2$: ß is a form factor lying roughly between 0.5 and 0.9, depending on the hull profile at the tail.

The skin friction component is taken as the total momentum flow being imparted to the wake. The total bare hull drag D_{ho} may then be roughly represented as:

$$D_{ho} \approx [(\beta\, \rho_a V^2 C_P')(\pi \delta t^2)/2] + \rho_a(\pi \delta t^2)(V - v_w)v_w \tag{14.27}$$

$$\underset{\text{(Form Drag)}}{\Downarrow} \qquad \underset{\text{(Surface Friction)}}{\Downarrow}$$

$$= \rho_a V^2(\pi \delta_{dt}^2)\{\beta C_P'/2 + (\delta_t/\delta_{dt})^2(v_w/V)[1-(v_w/V)]\} \tag{14.28}$$

or, the bare hull drag coefficient:

$$C_{Dho} = D_{ho}/\{[\rho a\, V^2 Q^{2/3}]/2\}$$

$$= (\pi \delta_{dt}^2/Q^{2/3})\{\beta C_P' + (\delta_t/\delta_{dt})^2(2v_w/V)[1-(v_w/V)]\} \tag{14.29}$$

where Q is the hull volume.

Most of the published data on the above parameters refer to wind tunnel model tests on classical rigid airship profiles: full scale boundary layer measurements are sparse and refer to the complete airship with all its appendages.

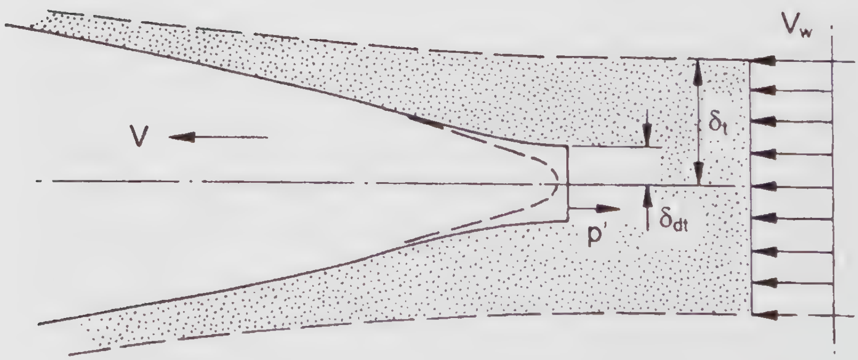


Figure 14.7. Idealised drag model.

From model tests, assuming for simplicity a 1/7 power law for the boundary layer profile, C_P' is about 0.8, ß for a 'sharp' tail is about 0.5, δ_t / δ_{dt} is 8 and v_w/V is 1/8, so that Equation 14.29 gives:

$$C_{Dho} \approx 45(\delta_{dt}/Q^{1/3})^2 \qquad (14.30)$$

and also shows that the skin friction drag is nearly 40 times the form drag. Model data indicate the ratio $\delta_{dt}/Q^{1/3}$ to be about 0.015-0.02, giving a C_{Dho} range of 0.01 to 0.02: this encompasses most measured values on a model scale. Full size values may be 15-25% lower because they correspond to much higher Reynolds numbers.

The key deductions from the above approximate analysis are that the form drag of the bare hull is insignificant compared with the skin friction component, and that the drag is roughly proportional to the square of the boundary layer thickness at the tail. It follows that any method of retarding boundary layer growth along the hull may lead to a significant reduction in drag and hence in the propulsive power requirement for a given speed. The viability of any such system must, however, depend upon how the saving in propulsive power compares with the internal power requirement of the boundary layer control system; the weight of the control installation must also be taken into account.

The most ambitious proposals for boundary layer control envisage laminar flow throughout, transition being prevented by suction through ports or slots distributed over the whole hull surface. The complexity of such an arrangement prohibits a simple generalised analysis, but an idea of the quantities involved is offered by a Boeing Vertol study of 1975, which looked at the parameters of such a system as applied to a hypothetical rigid airship of conventional geometry with a hull volume of 85,000 m^3 (3 m ft^3).

The study suggested that with laminar flow throughout the bare hull drag would be reduced by about 85% and the total drag by 65%. For a given airspeed, however, the ratio of the total installed power for both propulsion and boundary layer control to the propulsive power without boundary layer control was estimated to be 6.56 at 93 km/h (58 mph), 1.59 at 186 km/h (115 mph) and 0.55 at 372 km/h (230 mph): the break-even speed would be about 240 km/h (150 mph), which is too high for economic operation. Even more seriously, the weight of the control installation itself would be about half of the airship's gross lift.

The installation weight might be rather less for a monocoque hull, where ducting could be introduced within the existing sandwich core: in general, however, the concept of total laminar flow does not appear to be attainable in a commercially viable airship.

A less conventional but more promising approach was suggested in a 1974 paper describing an earlier Goodyear study using the arrangement shown in Figure 14.8.

Boundary layer growth, whether laminar or turbulent, is inhibited by a negative pressure gradient, so the hull profile in Figure 14.8 will minimise growth over most of its length by ensuring a constant fall in static pressure with distance from the nose. On arriving at the subsequent sudden narrowing of the hull and the corresponding sharp pressure rise the boundary layer would normally thicken sharply or separate completely, but it is effectively removed at this station by suction applied through an annular slot by a ducted propeller: the collected boundary layer is finally ejected as a propulsive slipstream.

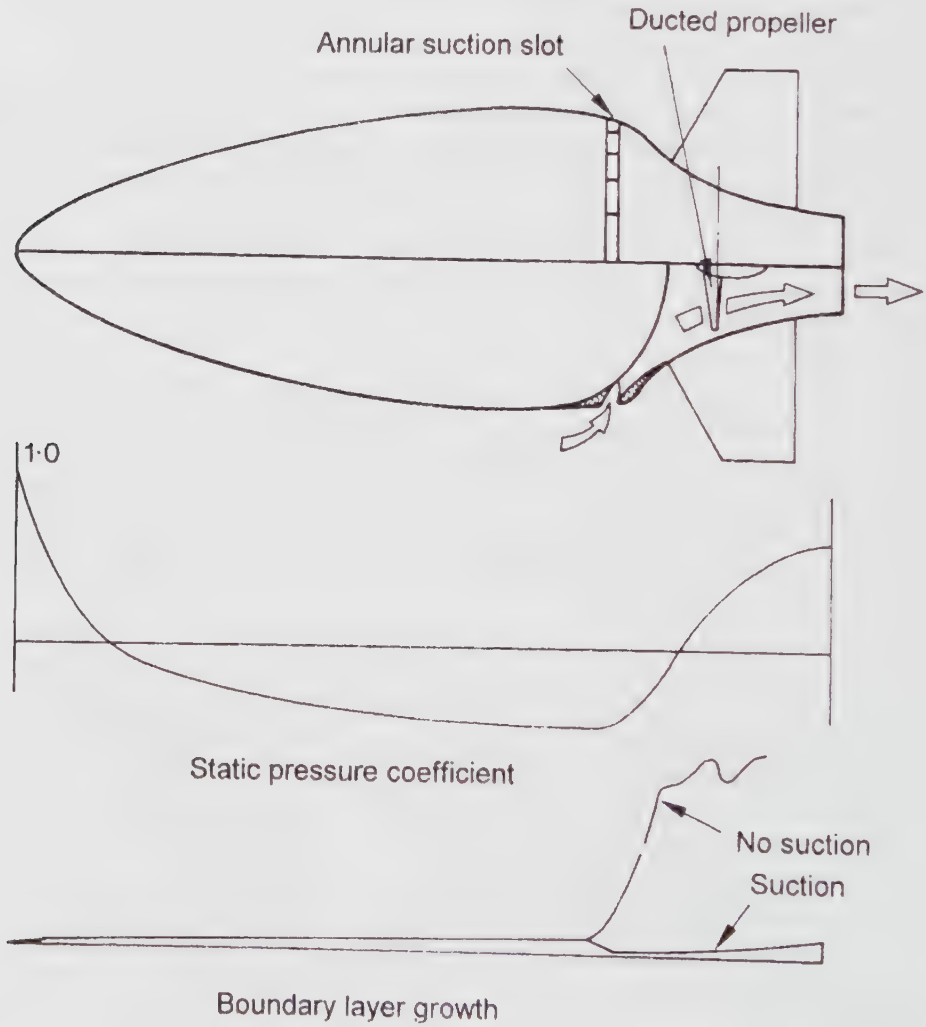


Figure 14.8. BLC Airship.

By localising boundary layer growth and applying suction only at the critical position in this way the power required for layer control is greatly reduced in comparison with an 'overall' suction system. The research programme on this concept indicated a total power saving, for a given speed, of 15-25% in comparison with a conventional airship of the same volume. There are however some adverse structural implications arising from the geometry, which places the weight of the tail surfaces and propulsion unit aft of the lifting hull; the propeller is also working in a difficult flow regime and would require a carefully optimised configuration.

STERN PROPULSION

The propulsive efficiency of a conventional propeller decreases as the incident flow velocity increases. If, therefore, an airship's propeller is taken from its usual position close to the hull flank, where the flow velocity relative to the propeller might be up to 10% faster than the speed of the airship, and repositioned in the wake immediately behind the tail, where the mean relative flow velocity could be 10-15% less than the airship speed, an improvement in thrust for a given power might be anticipated.

The potential gain, however, is conditioned by a number of factors, one of which is the propeller disc loading. Figure 14.9 shows, for conventional aircraft propellers, the variation of thrust per unit power, T/P, with axial flow velocity for different values of the disc loading factor P/D^2, where D is the propeller diameter.

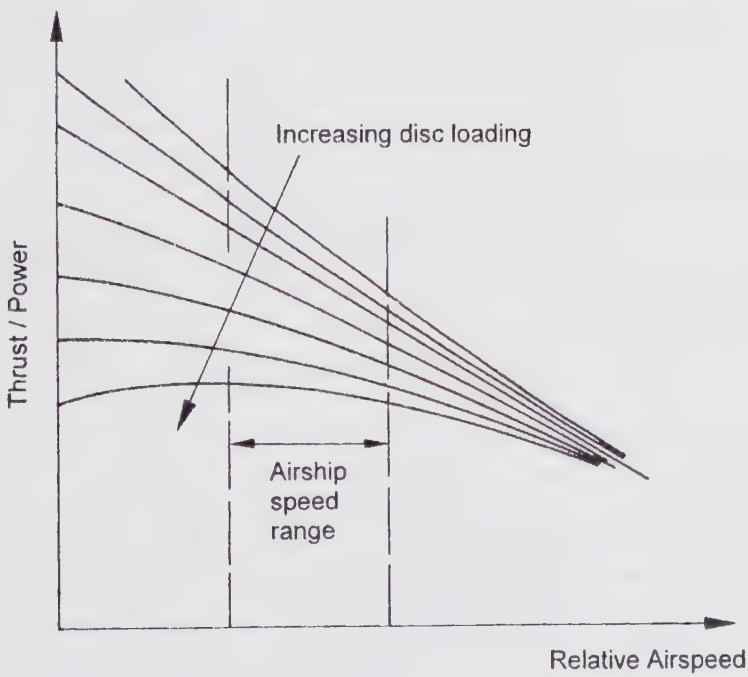


Figure 14.9. Conventional Propeller Characteristics.

Figure 14.9 indicates that the gain in thrust for a given fall in speed becomes less as the disc loading increases, and may in fact be reversed under very high loading. It follows that the thrust gain available from a stern-mounted propeller will be limited by the necessity for containing the propeller disc within the wake cross-section to gain an adequate airflow reduction; the diameter must remain relatively small and the disc loading correspondingly high, especially at higher speeds.

To illustrate the aerodynamic mechanism of stern propulsion, a very simple model will be used in which the power required by a stern propeller will be compared with that of a hypothetical conventional flank-mounted system for which the effective flow velocity is 1.05V, where V is the airspeed of the airship, and the disc loading P/D^2 - from a survey of historical data for conventional airships - is 40 N/m^2.

The wake diameter immediately behind the tail is taken to be $0.2Q^{1/3}$, where Q is the hull volume, and the stern propeller diameter is 80% of this diameter. Assuming a 1/7 power law for wake velocity distribution, the effective mean disc velocity is taken as the true velocity at 2/3 blade radius, and this is about 0.9V over the range of conditions to be considered. Using calibrated curves similar to those of Figure 14.9, it is then possible to construct the approximate curves presented in Figure 14.10, showing the proportional reduction in power requirement to be expected through the use of stern propulsion as a function of airspeed and envelope volume.

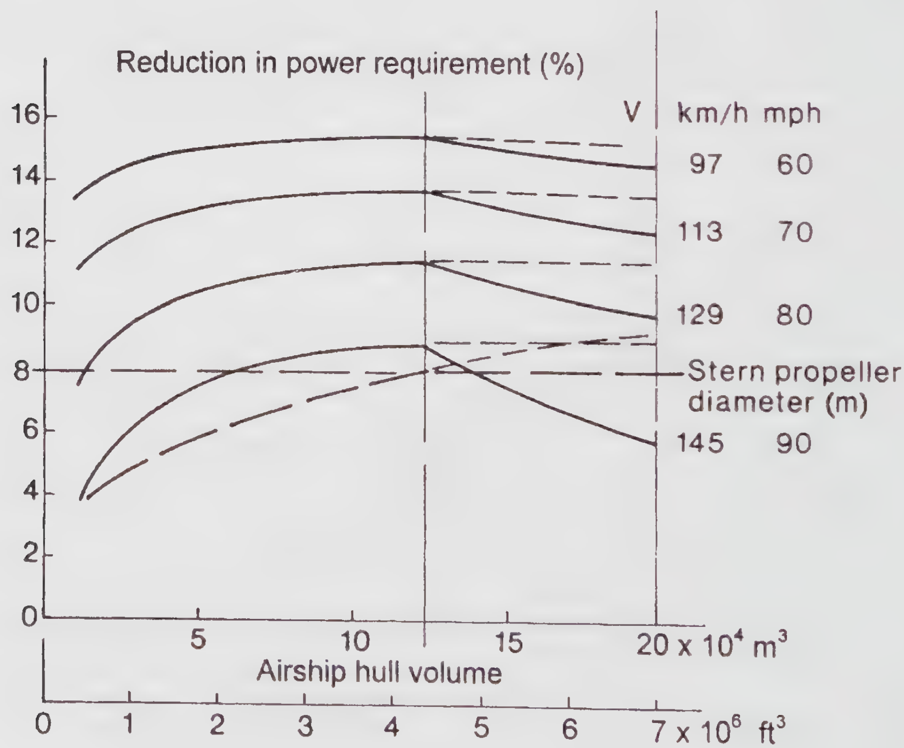


Figure 14.10. Reduction in Power Requirement using Stern Propulsion.

The required diameter of the single stern propeller is also shown, and this becomes large as airship size increases. It is assumed, for the sake of illustration, that the diameter is limited for practical reasons to 8.0m, and this reduces the power advantage for volumes above 125,000m^3 (4.4 million ft^3) because of the increasing disc loading.

The curves suggest that for large airships stern propulsion may reduce the power requirement by up to about 15% at 97 km/h (60 mph), 13% at 113 km/h (70 mph), 11% at 129 km/h (80 mph) and 9% at 145 km/h (90 mph), and therefore appear to substantiate the occasionally quoted claim of a general 10% advantage. The gain is substantially less for small airships because of the proportionally greater contribution of external installations to the overall drag, leading to a higher disc loading of the stern propeller for a given envelope volume.

The results summarised in Figure 14.10, however, depend critically upon a number of variable parameters. To begin with, the power advantage is referred to a traditional system of conventional flank-mounted propellers of a type basically designed for aeroplane applications. A modern airship could use larger low-speed wide-chord propellers or ducted fan units to improve efficiency. The effective base disc loading for the above comparison might therefore be practicably reduced from 40 to 30 N/m^2, and this alone would roughly halve all the percentage improvements shown. The measures suggested for the flank units would not be available for the stern propeller because of its diameter restrictions, though a ducted fan system has occasionally been proposed for stern propulsion and the BLC configuration of Figure 14.8 could in fact be regarded as one form of this.

A propeller at the stern would also affect the boundary layer approaching the tail: growth of the layer would be inhibited because the low pressure induced upstream of the propeller would reduce the adverse pressure gradient over the tailcone. The wake diameter would then be smaller and the propeller would also have to be smaller, raising the disc loading. If the wake diameter were reduced by 20% in the above analysis and the flank propeller loading from 40 to 30 as suggested, the apparent reduction in power requirement using stern propulsion would effectively disappear at 80 mph and be negative at higher speeds.

It may therefore be concluded that although stern propulsion in general could be expected to produce an improvement in propulsive power requirement, the gain could only be made worthwhile - set against the problems of installation weight and complexity - by careful optimisation of system design parameters for the particular airship concerned.

The few tests so far reported on stern propulsion have tended to be similarly inconclusive, and have also revealed a significant loss in thrust for a stern-powered airship in pitched flight, as when carrying a buoyancy discrepancy through dynamic lift. The performance of the stern propeller would in any case be less than ideal in the turbulence generated by fins and upstream external units, and vectored thrust, though useful for rudder and elevator augmentation, could not be used to moderate buoyancy to the extent available with existing flank-mounted vectoring units.

LENTICULAR GEOMETRY

The traditional airship configuration is still generally regarded as the optimum compromise between conflicting structural, aerodynamic and load-carrying requirements, but its sensitivity to crosswinds continues to present ground handling problems to which no totally satisfactory solutions have yet been found.

An alternative approach to the ground handling question is to reduce the lateral profile of the airship so that crosswind mooring may be effected without structural overload; various wide-bodied or multi-hulled geometries have been proposed to this end. Some of these designs are based upon a symmetrical lenticular form, sometimes inaccurately described as a 'flying saucer', and an approximate analysis of this configuration is presented in the following section

Looking first at the aerodynamic characteristics of the bare lenticular hull, it is found that its pendulum stability becomes inadequate to balance the aerodynamic pitching moment at a very low airspeed, at all speeds above which the bare hull is therefore unstable in pitch. Figure 14.11 shows the loading upon a lenticular hull moving horizontally with velocity V and pitched at a small angle α - exaggerated in Figure 14.11 - to its flight path.

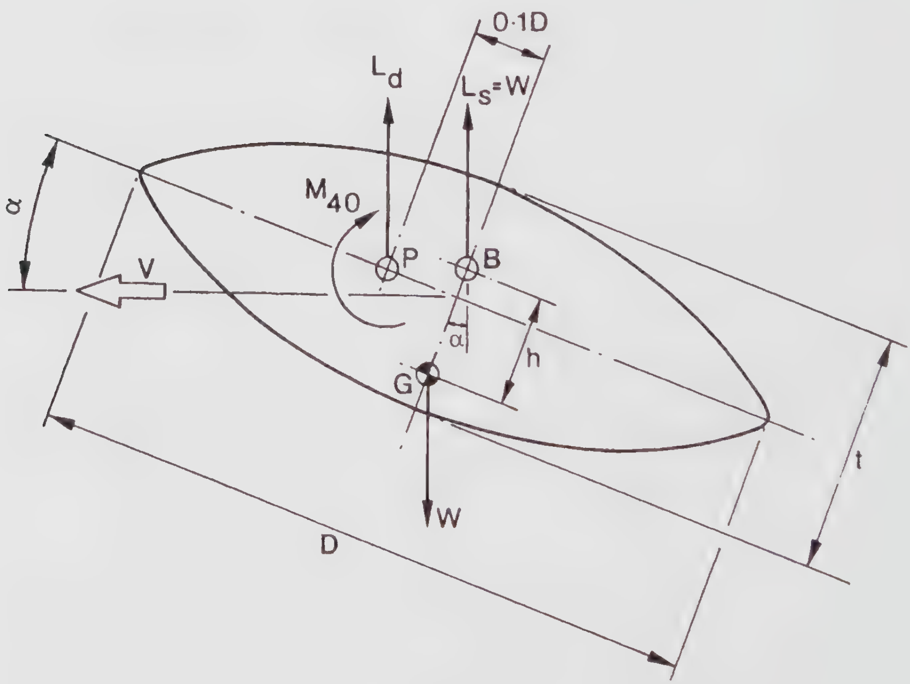


Figure 14.11. Lenticular Hull in Pitched Flight.

Neutral buoyancy is assumed, so that the static lift L_s acting through the centre of buoyancy B is equal to the weight W acting through the centre of gravity at G, B and G both lying on the axisymmetric axis. The aerodynamic datum P is at 40% chord: the corresponding nose-up pitching moment is M_{40} and the dynamic lift through P is L_d. The total nose-up moment about B, assuming α small enough for cosine effects to be negligible, is then $(M_{40}+0.1D.L_d-Wh\alpha)$, developing to:

$$M_b = 1/2\rho_a V^2 (\pi D^3/4)(\partial C_{M40}/\partial C_L)(\partial C_L/\partial\alpha)\alpha$$

$$+ 1/2\rho_a V^2(\pi D^2/4)(0.1D)(\partial C_L/\partial\alpha)\alpha - Wh\alpha$$

The static lift L_s is $I_o Q_g(\rho_a-\rho_g)$, where I_o is the sea level inflation fraction and Q is the hull volume, given by $Q = (t/D)\pi D^3/6$. Taking $t/D = ß$ and $h = nt = nßD$, it is found that the body will be unstable in pitch when the airspeed exceeds a critical value V_{crit} given by:

$$V_{crit}^2 = 80\, I_o g[1-(\rho_g/\rho_a)]ß^2 nD/\{6(\partial C_L/\partial\alpha)[1+10(\partial C_{M40}/\partial\alpha)]\} \qquad (14.31)$$

Wind tunnel data for a model with $ß = 0.325$ give the approximate values:

$$\partial C_T/\partial\alpha = 1.03 \quad \text{and} \quad C_{M40}/\partial\delta C_T = 0.4.$$

Taking $I_o = 0.9$, $\rho_g/\rho_a = 0.138$ and $n = 0.4$, Equation 14.31 reduces to:

$$V_{crit} = 0.912\sqrt{D} \text{ m/s (D in m)} \qquad (14.32)$$

Equation 14.32 shows that a lenticular hull of diameter 100m (330 ft), thickness 32.5m (107 ft) and volume 170×10^3 m^3 (6×10^6 ft^3) will become unstable in pitch at only about 33 km/h (20 mph). For a diameter of 50m (165 ft) the critical speed falls to about 23 km/h (14 mph). Marginal increases in the critical speed may be secured by, for example, concentrating payload, fuel, flight deck and engine cars below the hull to increase h, or by rearranging the internal gasbags to move B forward. Such measures, however, cannot be expected to bring the critical speed up to a reasonable cruising value without incurring unacceptable penalties in lift, weight and drag.

The principal problem of this geometry lies less with the instability itself than with the difficulty of correcting it. The bare hull of a conventional airship is even more unstable in both pitch and yaw, but compensation for these characteristics is readily obtained by means of tail fins extending through the boundary layer into the free airflow. It is far more difficult to find effective positions for control surfaces on the lenticular hull without incurring large penalties in structural weight. Typical arrangements that have been suggested are illustrated in Figure 14.12.

Figure 14.12(A) shows control flaps let into the trailing edge of the disc. These would need to be active, i.e. in continuous movement to counteract pitch excursions as they arise, and because the flaps lie within the thickest and most sluggish part of the boundary layer the range of movement would need to be large to have a useful effect; this would lead to the danger of total flow separation at the hinge line unless some blown flap arrangement could be incorporated to energise the boundary layer in the critical region.

Figure 14.12(B) indicates a more effective arrangement in which a separate horizontal stabiliser is raised clear of the boundary layer on two (or more) vertical fins. This, if large enough, would offer passive weathercock stability, but at considerable cost in structural weight. Correlation of the lift and pitching moment data used above show that the centre of pressure is roughly at the leading edge of the disc, so that a horizontal wing above the trailing edge would have to generate, for a given angle of pitch, the same lift as the bare hull. If a rectangular wing is considered with $\partial\delta C_L/\partial\delta\alpha = 5$, say, the wing area required is found to be, for a hull with $\beta = 0.325$, about $0.16D^2$: so a hull of diameter 50m would require a stabiliser area of 400 m^2 - for example 40m span and 10m chord - and this with its supports would add considerable weight.

Aerodynamic loading also becomes significant with this arrangement: for example at 130 km/h (80 mph) a nose-up pitch excursion of 10° through vertical gusting would impose an upward load of about 28 tonne on the above wing. The total dynamic lift on the airship would be twice this, causing an upward acceleration of about 2.8g. The corresponding dynamic lift and acceleration for a conventional airship of the same volume would only have about a third of these values. A further problem with the elevated stabiliser is the danger of a nose-up stall of the airship blanketing the wing in a stalled airflow region, thereby destroying its ability to correct the nose-up attitude.

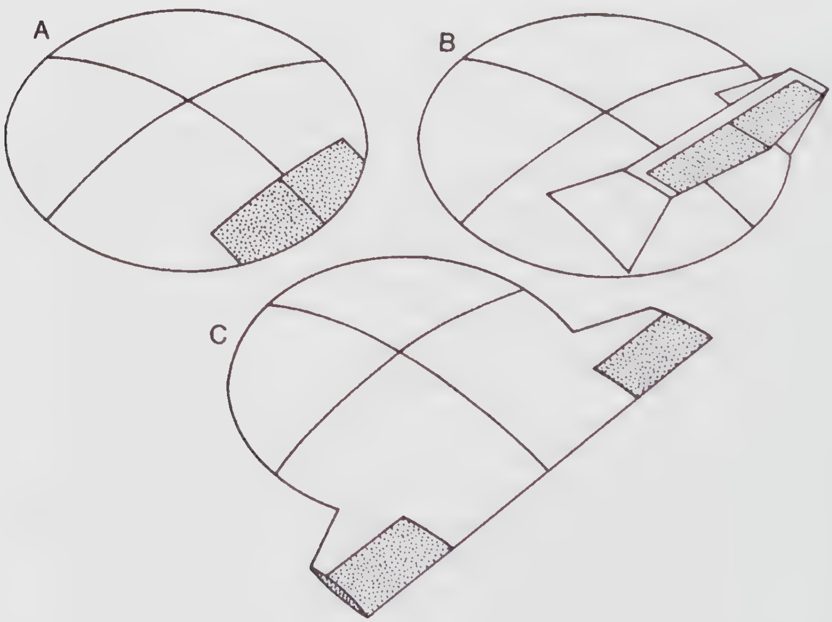


Figure 14.12. Stabilisation of Lenticular Hull.

The best solution from the aerodynamic point of view is that shown in Figure 14.12(C), where horizontal fins are cantilevered out from the trailing edge to reach the free stream beyond the zone of boundary layer and wake effects. The span across these fins must, however, be appreciably greater than the disc diameter in order to extend beyond the cores of the large tip vortices generated along the axial edges of the disc in pitched flight, as the inboard wash of these vortices would otherwise reduce the effective incidence of the fins and hence their restoring lift. The fins, which between them must carry about the same load as the raised wing of Figure 14.12(C) (28 tonne for the case quoted), will be subjected to large bending effects and hence involve a correspondingly high structural weight penalty.

A further problem with the lenticular concept is the high drag generated by the geometry in comparison with that of a conventional hull of the same volume. This arises not only from the higher surface-volume ratio (typically by a factor of about 1.3-1.5) but also from the mechanism of drag generation explained in Figure 14.13.

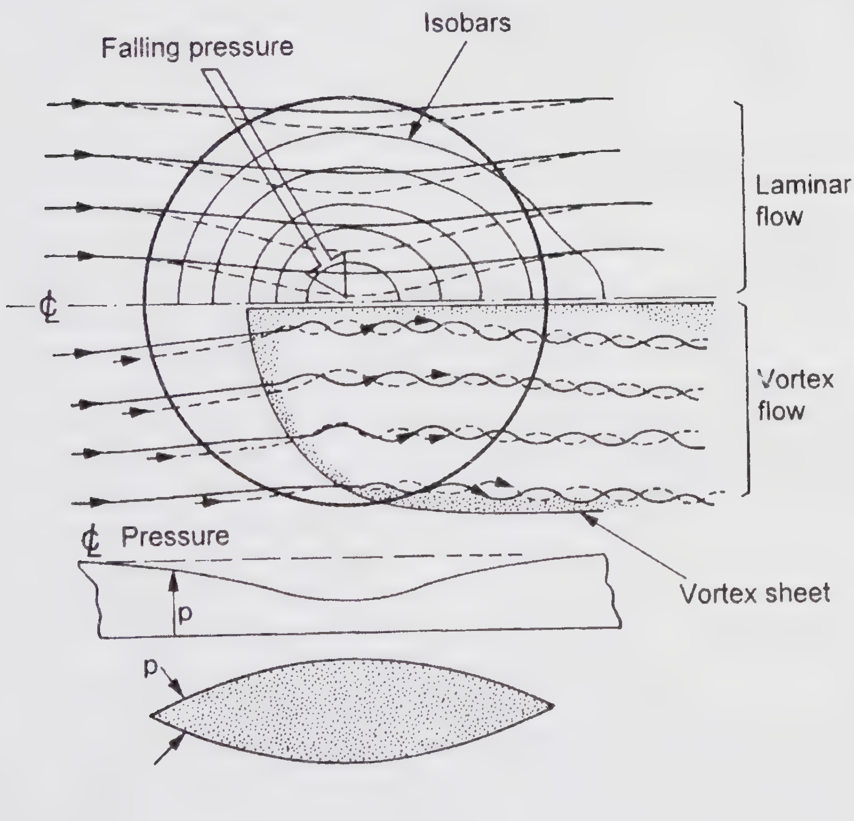


Figure 14.13. Drag of Lenticular Hull.

The static pressure p on the surface of the lenticular hull in unpitched flight decreases towards a minimum at the planform centre along both the axial and the lateral diameters. The latter effect generates a pressure gradient pushing streamlines inward over the leading half and back again over the trailing half, as shown in the upper half of the plan view in Figure 14.13.

Since, relative to the hull, layers of air within the boundary layer move more slowly the closer they are to the surface, these closer layers will be diverted to a greater extent by the pressure gradient, as indicated by the broken lines in the Figure. If the boundary layer could remain laminar the above behaviour would have no significant effect. In practice, however, the transverse velocity shear set up within the layer causes the flow to break up into a sheet of small vortices, as shown in the lower part of the plan view, and this vortex sheet absorbs energy to generate considerably more drag than would an equivalent axisymmetric profile.

None of the factors outlined above would prevent the realisation of a practicable lenticular airship, but they would all contribute to increased structural weight and a greater power requirement for a given speed, implying heavier propulsive units and fuel load. The total loss of payload would then have to be considered against the economic advantages of simpler ground handling procedures.

15

Unconventional Designs

G. Khoury

INTRODUCTION

The Oxford Dictionary defines the word *unconventional* as "not bound by convention or custom". In airship terms this broad definition renders unconventional a whole range of novel designs. A design may be regarded as conventional after its consistent production and mainstream application over a period of time.

However, the introduction of state-of-the-art materials, components and systems can generally be considered as a normal part of technological evolutionary development of conventional airships. For example, this could apply to fly-by-light control, bow thrusters for automatic docking, and the use of Kevlar material in the gondola.

Unconventionality may, however, be attributed to an airship if a major feature of the design is significantly altered from the 'conventional', such as the overall shape, method of lift, source of power, structural configuration, type of lifting gas, or mode of control.

The airship designs proposed have been so diverse that only the broadest categorisation is possible, as tentatively suggested in Table 15.1. It should be noted that the proposed categorisation is by no means all-inclusive and can be subject to alterations according to personal preference and historical development.

A detailed treatment of the many unconventional designs is beyond the scope of this chapter. Features of unconventional designs proposed to date are briefly discussed under headings related to the major feature in the design that is altered. A more detailed mathematical analysis is, however, given for the cases of the lenticular and solar-powered airships in Chapters 14 and 16 respectively.

SHAPE

Conventional

The shape of the envelope has a major influence on its overall performance. Ideally, the surface area should be as small as possible relative to the volume since the envelope weight is largely proportional to the surface area while the lift is proportional to the volume. For a reasonably streamlined overall shape, the air resistance is also determined primarily by the surface area.

Table 15.1. *Categorisation of airships into conventional and unconventional designs*

Design Feature	Airship	
	Conventional	Unconventional
Shape	'Ellipsoidal'	Dart Deltoid Flat body Lenticular Multi-balloon Multi-hull Spherical Toroidal Winged hull
Lift	Aerostatic Lift-augmented	Hybrid (Powered Payload)*
Power Source	Petroleum fuel	Electrical Human Hydrogen Microwave Nuclear Solar
Structure	Non-rigid Rigid framework#	Metal-clad Pressurised (inflated) tube Rigid monocoque Semi-rigid#
Gas	Helium Hydrogen#	Hot air Methane
Control	Manned	Unmanned remotely piloted: low/high altitude
Payload	<50t	50-500t (Heavy Lift)

\# Primarily before World War II

* Dynastats: *Dynairship, Megalifter, Dinosaure, AirCruiser*
Rotastats: *Heli-stat, Helicostat, Heliship, Helitruck, SLAB, Toroids*
Rotating Hull: *Cyclocrane, Aerocrane, Magnus Aerolift*

A spherical shape provides the optimum lift efficiency. Departures from this optimum should utilise shapes based on circular arc sections to minimise surface stresses. A comparison of envelope area relative to the sphere for different shaped airships having the same volume (Figure 15.1) indicates that the conventional streamlined shape has significant advantages in this respect over both the multi-hulled and lenticular designs.

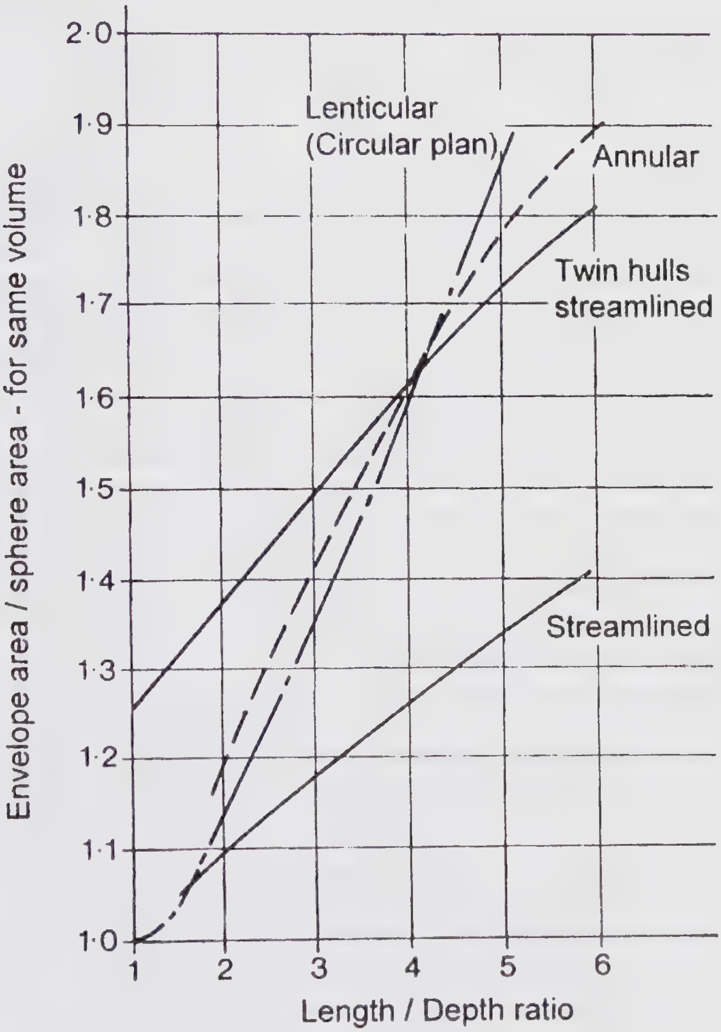


Figure 15.1. Envelope area relative to sphere for same volume (Howe, 1991).

The conventional airship shape closely approximates to a streamlined body of revolution about a longitudinal axis. It is generally accepted that the conventional streamlined shape provides the optimum compromise between the conflicting aerodynamic, static lift and structural requirements. It is the most efficient shape for an immersed body moving through a fluid. An important geometric parameter in conventional airship design is the length/diameter ratio which can be optimised in terms of drag and structural weight for a given volume.

The conventional shape is, however, less efficient than the sphere in terms of lift and is sensitive to crosswinds thus presenting problems during mooring and at low speeds. It is also associated in the minds of some people with the failed designs of the past. Consequently, there have been frequent attempts to alter the envelope shape for reasons of function, cost or style.

Lenticular

One of the most frequent configurations suggested has been an envelope geometry based on a body of revolution about a vertical axis. This 'lenticular' shape, is more commonly but less accurately described as the 'Flying Saucer'. It offers a 'futuristic' appearance, provides a lifting body shape, its payload space is not stretched along a narrow keel, and it presents a reduced lateral profile to crosswinds and thus is less susceptible to structural overload during mooring. A problem associated with this concept is the difficulty of minimising the length to depth ratio for a given enclosed volume. Aerodynamically, the bare lenticular hull's stability can become inadequate to balance the aerodynamic pitching moment. A further problem of the lenticular concept is the high drag generated by the geometry in comparison with that of a conventional hull of the same volume. Measures to address these problems are available but may contribute to increased structural weight and a greater power requirement for a given speed (see Chapter 14 for further details). Lenticular airships (Figure 15.2) designs include:

The British *Skyship* (West, 1975). A 9m radio controlled model Skyship was built by Thermo Skyships and was flown in the large hangar at Cardington in 1975.

Two very large lenticular designs (Balaskovic, 1975) called *Pegasus* (300m dia) and *Titan* (235m dia) were studied in the early 1970s by a French consortium headed by the Centre National de Recherche Scientifique (CNRS). Pegasus was designed as an unmanned 21 km high altitude airship for geophysical research driven by 'live thrust' vectoring propellers powered by DC electric motors drawing current from hydrogen cells. Titan was designed as a 'flying crane' with a built-in hoist to carry loads up to 900 tonne over distances up to 1000 km. It would have used diesel-driven fans to push air jets through vectoring ducts. Neither design was built.

The Mexican *Spacial MLA-32-B Toluca* (Roldan, 1986). The Spacial company built a full-size 32 m diameter (5,940 m^3 volume) saucer airship with a low altitude payload of 2.2 tonne and a gondola for a pilot and five passengers. The hull comprised a Kevlar-covered aluminium frame housing six gasbags. The airship was under-powered employing two 67 kW engines driving vectoring ducted propellers and was expected to fly at 75 km/h with an endurance of 3 hours. The airship made its first and only manned flight in 1989.

A Russian lenticular design called *Thermoplane* (Ishkov and Panyaev, 1993) was proposed to carry heavy loads to remote regions of Russia not serviced with complex ground bases, hangars or mooring masts. Its promoters state that the airship employs the largest carbon ribbon composite structure in the world. A sketch of the elevons indicates that they have been placed in an optimal position (see Chapter 14).

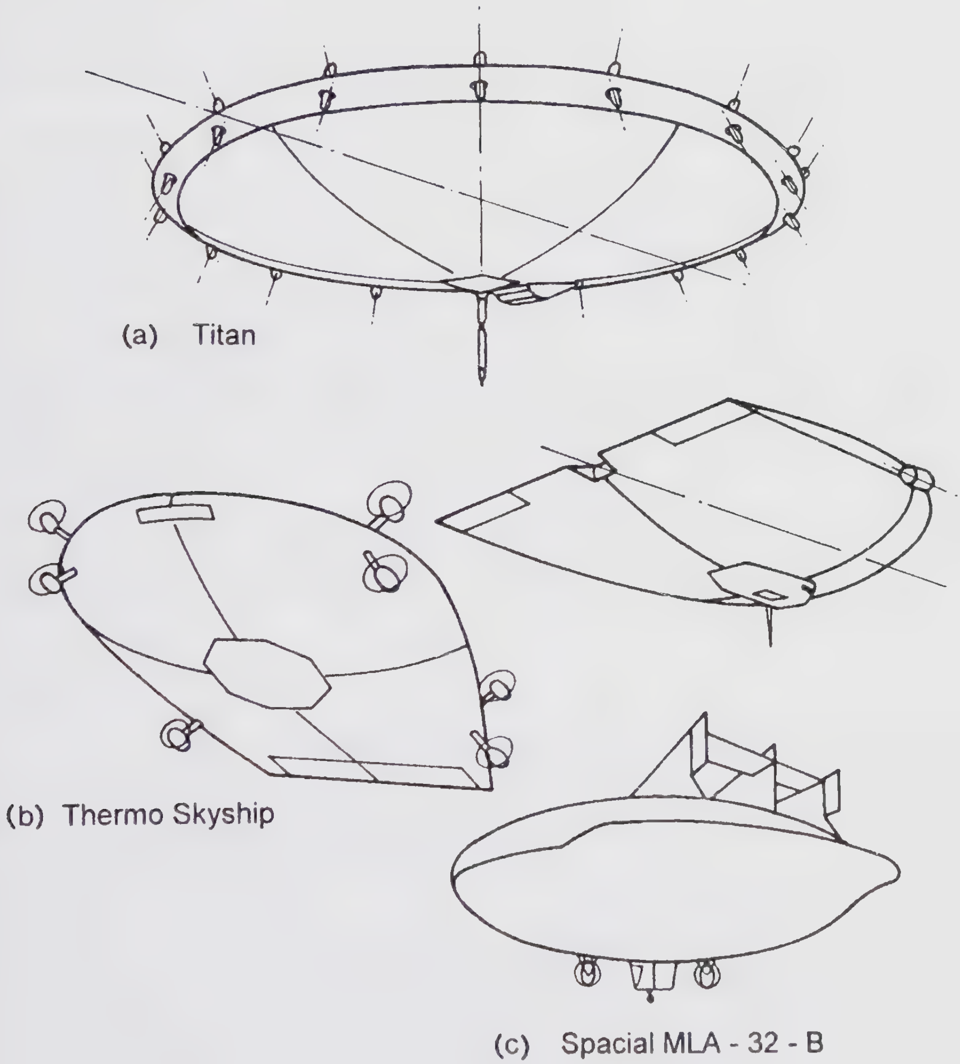


Figure 15.2. Lenticular airship designs (Mowforth 1991).

Deltoid, Winged-Hull, Flat-Body

The majority of conventional airships make some use of the aerodynamic lift generated by the 'ellipsoidal' body. There have, however, been a number of proposals where the conventional envelope shape has been significantly altered to produce much greater aerodynamic lift than is normally available. Some of these suggest a winged hull such as the Ames *Megalifter* (Fink, 1974) but most proposals suggest the use of a low aspect ratio deltoid planform for the envelope such as the Aereon *Dynairship* (Miller, 1975) (Sheldon, 1985), or a shape similar to that developed for lifting body spacecraft. Flattened-body airship designs (Figure 15.3) have also been proposed (Gibbens, 1984) which would facilitate cross-wind mooring, provide aerodynamic lift, require a lower hangar roof than an equivalent conventional airship, but are structurally less efficient.

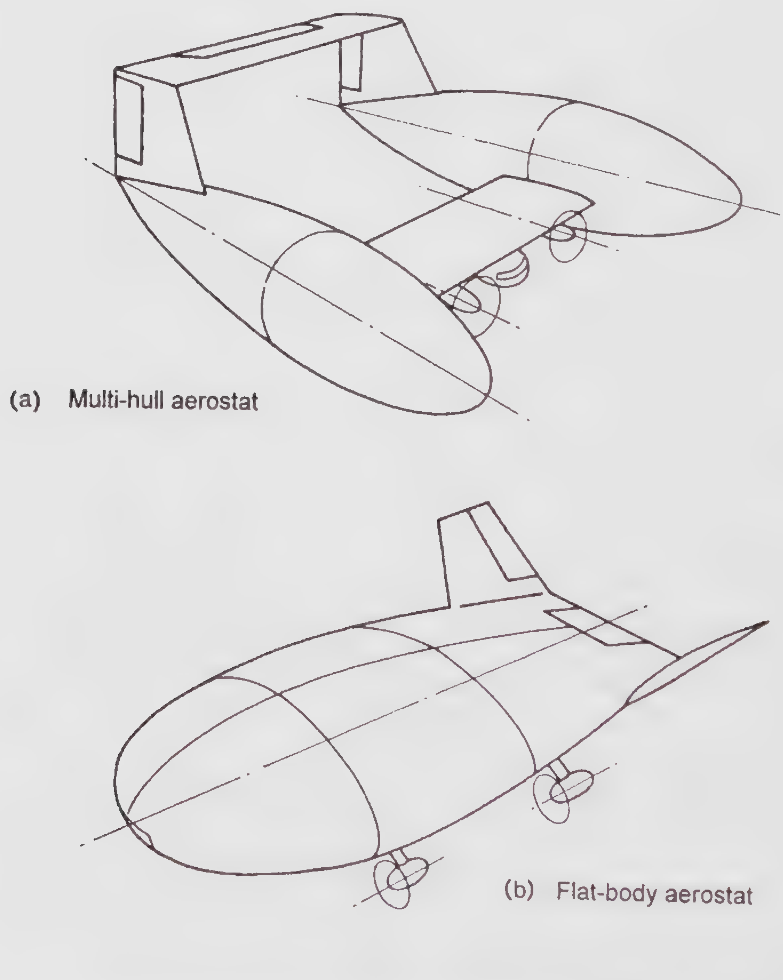


Figure 15.3. Flat-body, and Multi-hull airship shapes (Mowforth 1991).

Dart

The High-Altitude Long Range Observation Platform (*HALROP*), designed by Onda in Japan, has a dart-shaped hull with a long tail boom and a cross-shaped tail-wing at the end of the tail boom. Such a hull structure is adopted to give the airship the ability to stay for a long period of time in the stratosphere. For this purpose, the aim of the design is to provide the airship with a high-wind performance by achieving a high propulsion efficiency at the expense of manoeuvrability and ability for circling (Onda, 1995).

Multi-hull

Multiple-hull arrangements (Figure 15.3) may have the advantage of the simpler construction of smaller units. There is a weight penalty, however, because the surface is greater than that of a single hull for a given total volume and the same length-to-diameter ratio. The overall reduction in size might enable a compensating weight saving to be achieved, but the multi-hull layout may also be difficult to handle in turbulence. The airship's suspension mechanism in air is very different from that of a more stable multi-hull boat floating on water.

The US Aereon Company designed a triple-hull airship in the early 1960s to explore the practical possibilities of using fully the dynamic lift of airship hulls (Miller, 1975) but came to the conclusion that a deltoid planform would provide a more efficient lifting-body shape.

Twin-hull airships have also been proposed in a hybrid configuration in which the rotors provide dynamic lift (White, 1973) (Andoh, 1989). Allen (1974) has described a twin-hull configuration for forestry use.

Spherical

A spherical shape has also been proposed for applications where lift efficiency and cost, rather than speed, are the important parameters. The relatively high drag coefficient on a spherical airship, compared with the conventional cigar-shaped ship, limits the top practical speed to a modest 30 knots.

Positive features promoted by the TCOM company (Baesha. and Euler, 1992) include optimum buoyant lift-to-weight ratio, a maximum skin hoop stress half that of a cylinder of the same diameter, simple manufacture due to absence of fins, and simpler winching and mooring systems with no weather vaneing requirement.

The 21st Century Airships Inc. of Newmarket, Ontario has flown in 1994 a 19.5 m spherical airship *SPAS-4* capable of carrying a pilot and ten passengers on leisurely sightseeing rides (Colting, 1994). Varied and deflected thrust from the airship's two engines provides the airship with helicopter-like manoeuvrability which allows the airship to hover and make 360° turns. Both steering and altitude controls are achieved without fins, rudders and elevators. The pilot and passengers are seated inside the envelope in a spacious cabin enhanced by 13 tinted windows. This is done to (a) reduce the drag coefficient from 0.25 to 0.18, (b) create more spacious, quiet and comfortable accommodation and (c) provide a striking appearance. The promoters state that spherical airships are less expensive, both to manufacture and operate, than conventional cigar-shaped airships.

A rotating spherical hull has also been proposed for providing additional Magnus lift (see below).

Toroidal, Multi-balloon, SLAB

A range of other unconventional shapes have been proposed for applications in which cruise efficiency is largely subordinate to the requirements of lift. These will be discussed in more detail below and include multi-balloon, giant *SLAB* and toroidal configurations employing rotors for powered lift.

LIFT

Conventional

The conventional airship is a simple displacement vehicle with vertical take-off and landing (VTOL) capability, but in practice aerodynamic forces are necessary for both low and higher speed control. Conventional airships may rely on a degree of dynamic lift augmentation (through envelope shape and/or vectored thrust) for 'heavy' flight, but the bulk of the structure and payload are carried by static lift. Consequently, it cannot achieve large controlled variation in lift in excess of that obtained through vectored thrust.

Although the airship has the potential of lifting very large loads and carrying them economically at modest speeds, such operations require a relatively large airship with the attendant problems of structural design and low speed control.

The conventional airship is also vulnerable to wind on the ground, while the operation of loading and unloading is difficult.

Hybrid Airships

The foregoing considerations have led to the concept of a 'hybrid' airship which combines features of both lighter- and heavier-than-air craft. The short take-off and landing (STOL) 'dynastat' hybrid is a cross between an airship and an aeroplane, while the vertical take-off and landing (VTOL) 'rotastat' hybrid is a cross between an airship and a helicopter. A simplified representation for purposes of definition only is given in Figure 15.4. The dynastat may be best suited for transport applications while the rotastat may be best suited as a 'flying crane' to carry large loads at lower speeds, and shorter distances, than a dynastat.

Both hybrid types dispense with the use of ballast and greatly improve ground handling and load exchange. They are also smaller in size than the conventional airship for the same payload.

A whole range of novel and imaginative hybrid designs have thus been proposed which provide powered lift well in excess of that achieved by vectored thrust in conventional airships. In these hybrid airships, the gas lift largely supports the unloaded weight of the vehicle, while the powered lift largely supports the payload.

Hybrid airships also improve on some features of the parent heavier-than-air craft. For example, a fundamental problem of helicopter design is the large proportion of available rotor lift that must be set aside to lift the vehicle itself (the gross lift of the Sikorsky 64 is 20 tonnes of which the vehicle weighs 11 tonnes), whilst the aeroplane requires long take-off and landing runways.

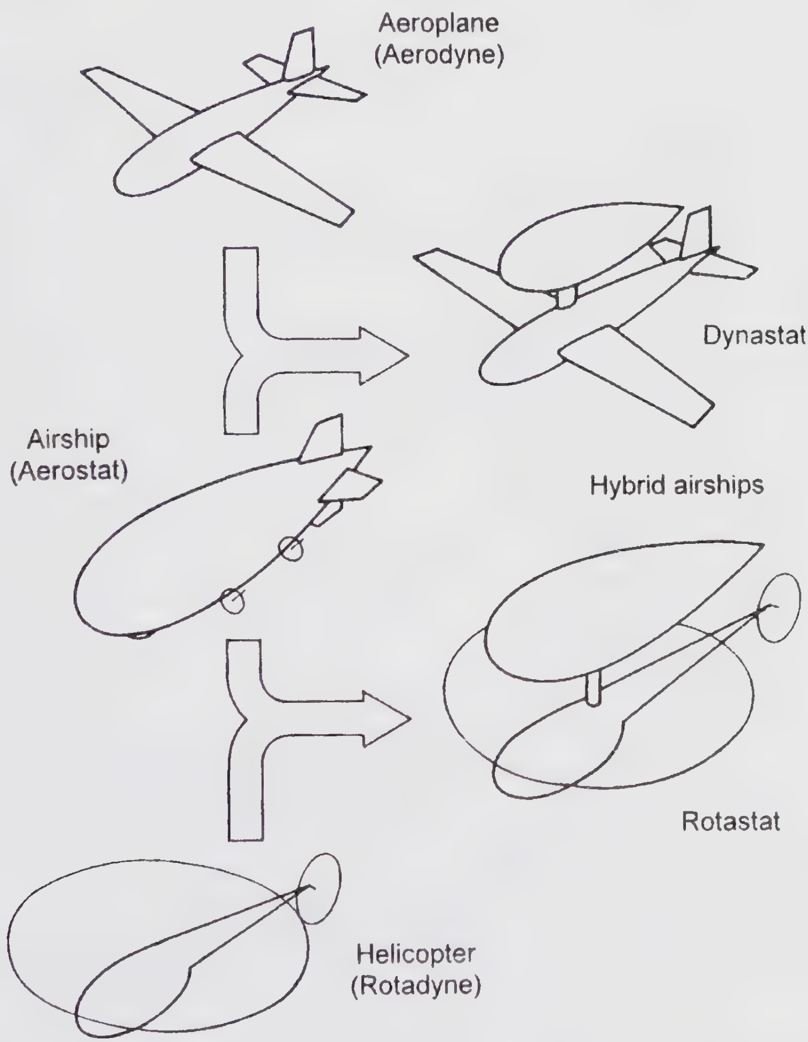


Figure 15.4. Hybrid airship types (Mowforth, 1991).

The position of the airship in the total V/STOL aeronautical spectrum is shown in Figure 15.5. The lift versus speed relationship is shown for various V/STOL systems using the helicopter as the starting point. Speed increases lead towards jet lift VTOL by way of compound helicopters and fan lift V/STOL. However, if lift is the main criterion, then the path is towards the large cargo airship through the heavy lift helicopter (H.L.H.) and the hybrid airship (Howe, 1991).

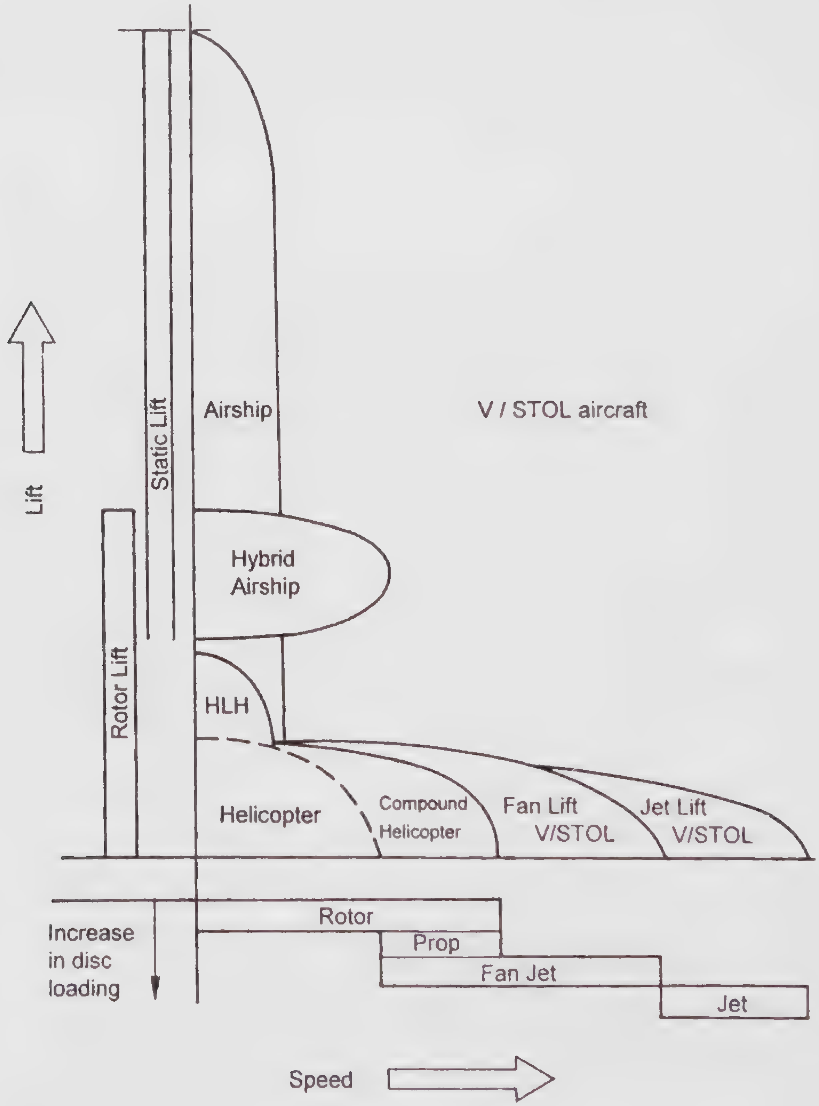


Figure 15.5. The V/STOL Spectrum (Howe, 1991).

Dynastats (Winged Hulls, Deltoid, Lenticular, Flat-Body)

If STOL rather than VTOL performance is accepted, then it becomes possible to consider designing a more aerodynamically efficient airship so that the lifting gas carries the dead weight and the dynamic lift carries the disposable load. The ballast can then be dispensed with.

In terms of specific power per unit lift, the dynastat hybrid airship is shown in the Gabrielli von Karman plot (Figure 15.6) to fill the gap in the 100-200 mph speed range between the conventional airship at lower speeds and the subsonic aircraft at higher speeds.

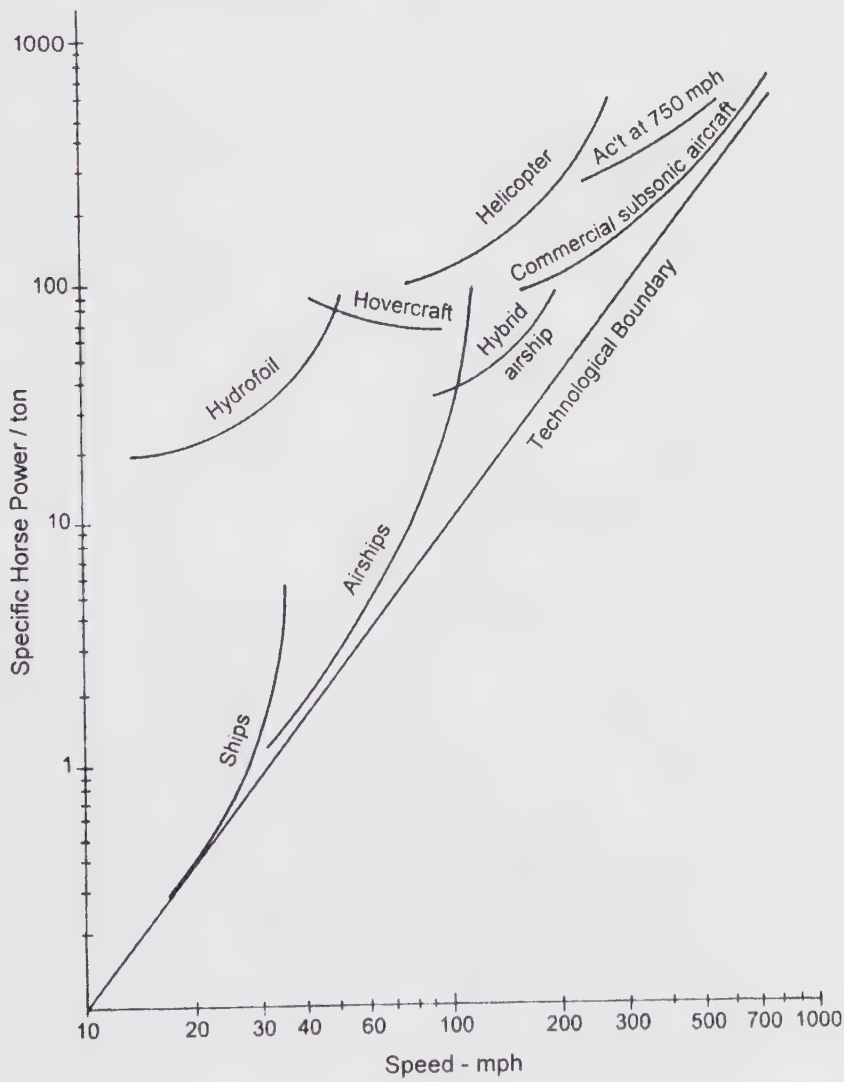
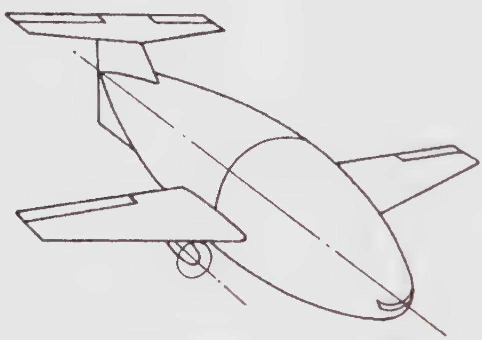


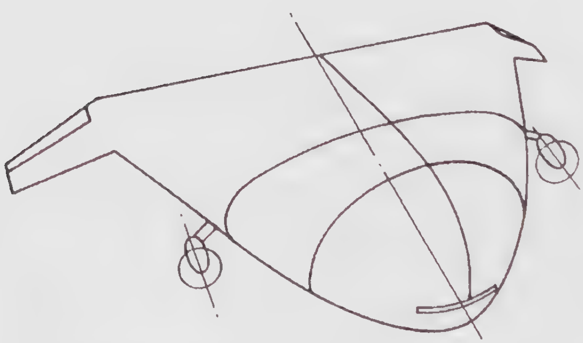
Figure 15.6. Comparison of transport systems (Shaw, 1991).

The fuel efficiency of the dynastat is shown to be higher than the helicopter within the same speed range. The diagram also shows that the conventional airship is one of the most viable craft between 30 knots and 120 knots (Shaw, 1991).

The advantage of the dynastat occurs in the landing and loading phases of its operations which are far less complex than for a conventional airship. Operationally, the craft may be considered as a STOL vehicle with an effectively low 'wing' loading. The advantages of VTOL in a conventional airship are exchanged in the dynastat for greater lifting capacity for a given aerostatic lift, and for easier low speed control. Nevertheless, an STOL hybrid airship does lose the important VTOL capability. There could also be problems associated with the design of adequate pressure resistant structures. Dynastat hybrid design proposals have come in four configurations:



(a) Winged-hull Dynastat



(b) Lifting-body Dynastat

Figure 15.7. Winged-hull and Lifting-body dynastats (Mowforth, 1991).

Winged Hulls (Figure 15.7): Wings are attached to conventional shaped hulls as in the case of the very large 200,000 m^3 Ames *Megalifter* (Fink, 1974) which was not built (Figure 15.8). Half the lift would have been provided aerodynamically. The plan was to make use of numerous standard aircraft components combined with a soft-skin lifting body. Winged airships are expected to possess handling qualities similar to those of an aeroplane. The concentrated wing loads on the airship hull, and the anticipated faster speeds, will necessitate strengthening of the structure with attendant weight penalties. Winged hull airships cannot, therefore, utilise the diffuse lightweight structure characteristic of conventional airships.

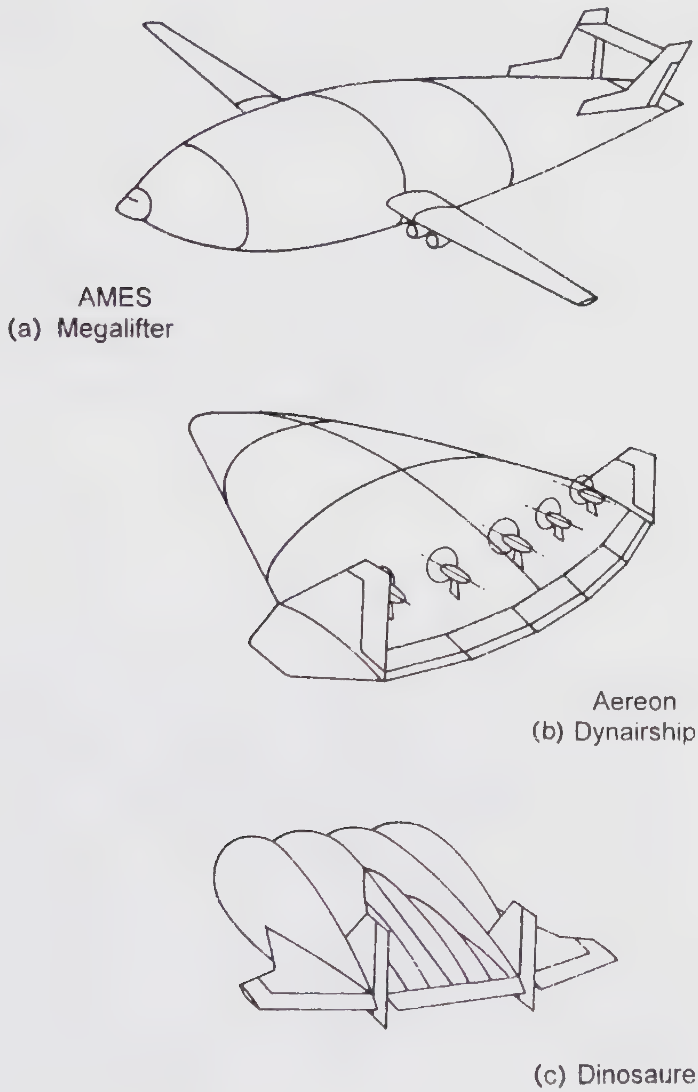


Figure 15.8. Megalifter, Dynairship, and Dinosaure dynastats (Mowforth, 1991).

Lifting-Body (Figure 15.7): Flat-body airships facilitate cross-wind mooring and accommodation under cover, but would be structurally less efficient than conventional airships. The lifting-body dynastat distributes the lift more evenly than a winged-hull dynastat, but there is still a weight penalty associated with its large surface/volume ratio.

A 'flying wing' delta planform shape hybrid airship called *Dynairship* has been proposed by the *Aereon Corporation* (Figure 15.8) to provide an efficient lifting body (Miller, 1975) (Sheldon, 1985)). A small experimental manned version *Aeron 26* was successfully flown in 1971 as an 'aerodynamic proof of the concept' prototype. Keith Stewart proposed the *AirCruiser* to be constructed around a framework of inflatable airbeams which are strong and resilient. (Airship, no. 108, June 1995). The first commercial version is anticipated to be 60 m long and able to travel at 64 km/h for sightseeing duties and 322 km/h for transport applications.

Lenticular (Figure 15.2): Another popular lifting body concept is the lenticular hull described above and in Chapter 14.

Multi-Lobe (Figure 15.8): A multilobe non-rigid pressure airship of flattened geometry called *Dinosaure* was proposed in the early 1980s by a French consortium under the direction of EERM intended for atmospheric research. Suction pads placed beneath the hull were to be used during mooring. A half-size radio-controlled model was successfully flown. The multi-lobe airship offers aerofoil characteristics for operation as a dynastat but suffers a weight penalty associated with its large surface/volume ratio.

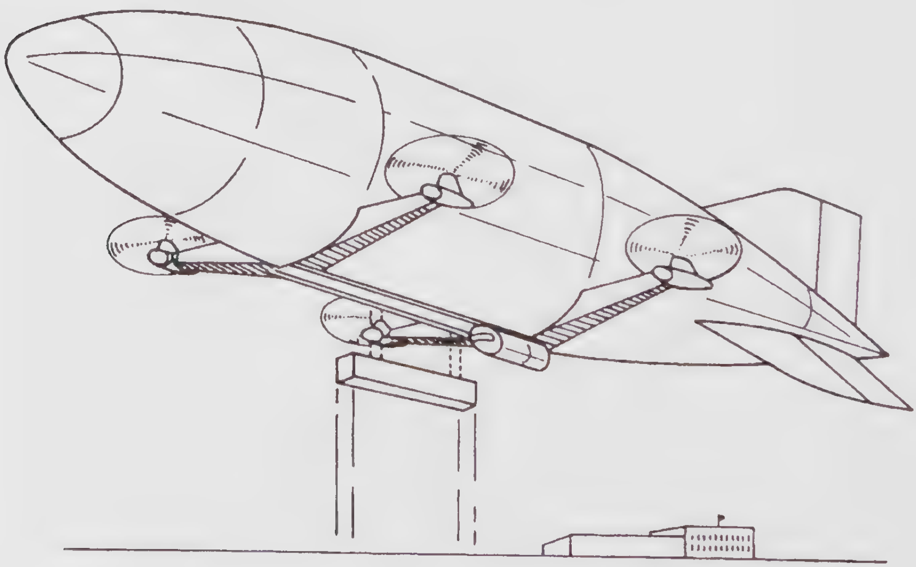


Figure 15.9. Four rotor rotastat (Howe, 1975).

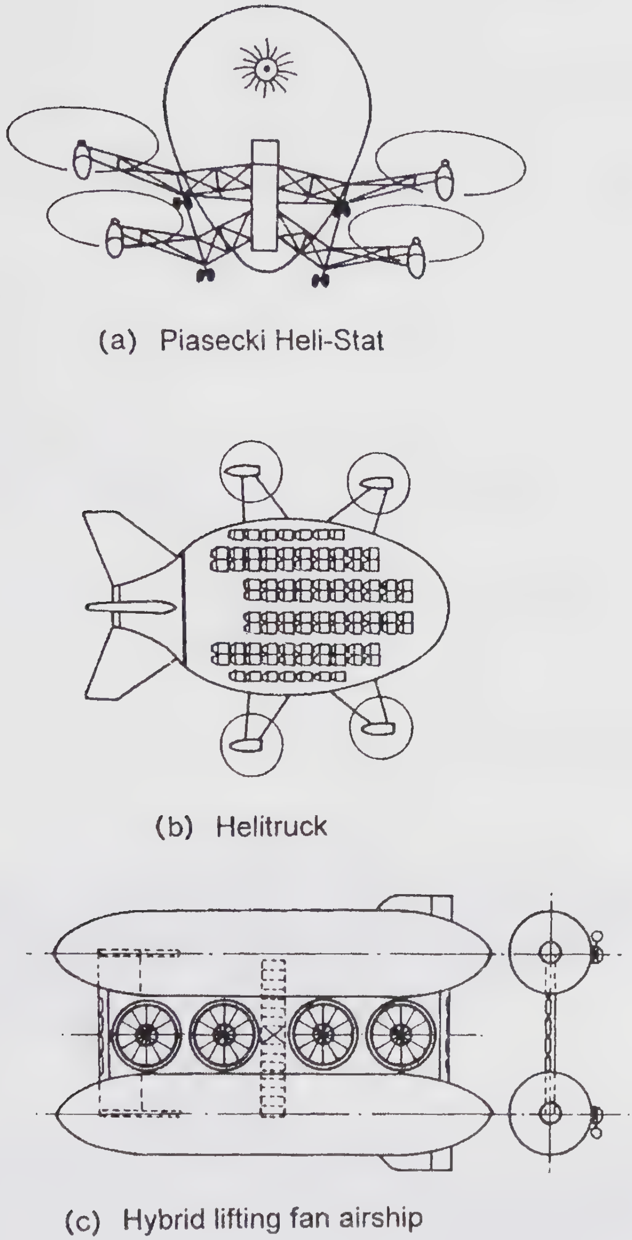


Figure 15.10. (a) Heli-Stat, (b) Helitruck, and (c) Stewart's 4-rotor rotastats.

Rotastats (Four-, Twin-, and Single-Rotors)

Rotastat hybrid airships essentially combine aerostatic 'airship' lift for the structure with 'helicopter' type vertical rotor thrust for payload lift. The major advantage of VTOL capability is thus maintained, but at penalty costs in cruise efficiency and fuel requirements.

Lifting rotors were employed in a number of French airship designs by Zodiac and Oehmichen in the 1920s and 1930s to provided significant vertical lift control. Separate propellers provided axial propulsion. Proposals since the early 1970s have come essentially in four configurations:

Four Rotors (Figure 15.9) are normally attached to the bottom of a conventional airship hull. Such designs include Howe's "*Minimum Development Rotor Airship*" (Howe, 1975), the Goodyear proposal (Phoenix, 1976) and the German/US rigid *Helitruck* (Figure 15.10) proposed by Bothe in the early 1980s (Behrendt and Skudelny, 1985).

The US *Heli-Stat* was first proposed in 1974 by Piasecki for forestry logging operations (Airship, June 1980). A prototype consisting of four helicopters with interlinked controls attached to a conventional airship hull was completed in 1986 (Figure 15.11). The prototype was, however, destroyed in experiment. Reports on the failure were published in the journal Airship in the September 1986 and June 1988 issues. They suggest that a missing throttle linkage pin, ground handling difficulties and inadequate design were blamed for the loss of the hybrid airship.

Figure 15.11. Piasecki's Heli-Stat.

An altogether different design is a four-rotor proposal by K. Stewart from New Zealand (Airship, June 1985) comprising a twin-hull airship with four lift fans attached in between. The fans are contra-rotating to provide stabilisation. Four separate tiltable ducted propellers provide forward thrust and mobility.

Twin Rotor hybrids (Figure 15.12): The failure with the four rotor Heli-Stat has led some to conclude that a twin-rotor system may be more practical, using either one rotor on either side of the hull or tandem rotors between twin hulls. An example of the former design is the French *Helicostat* (Air et Cosmos, 8 Jan.1977), while the latter is exemplified by the Japanese twin-hulled *Heliship* (Andoh, 1989).

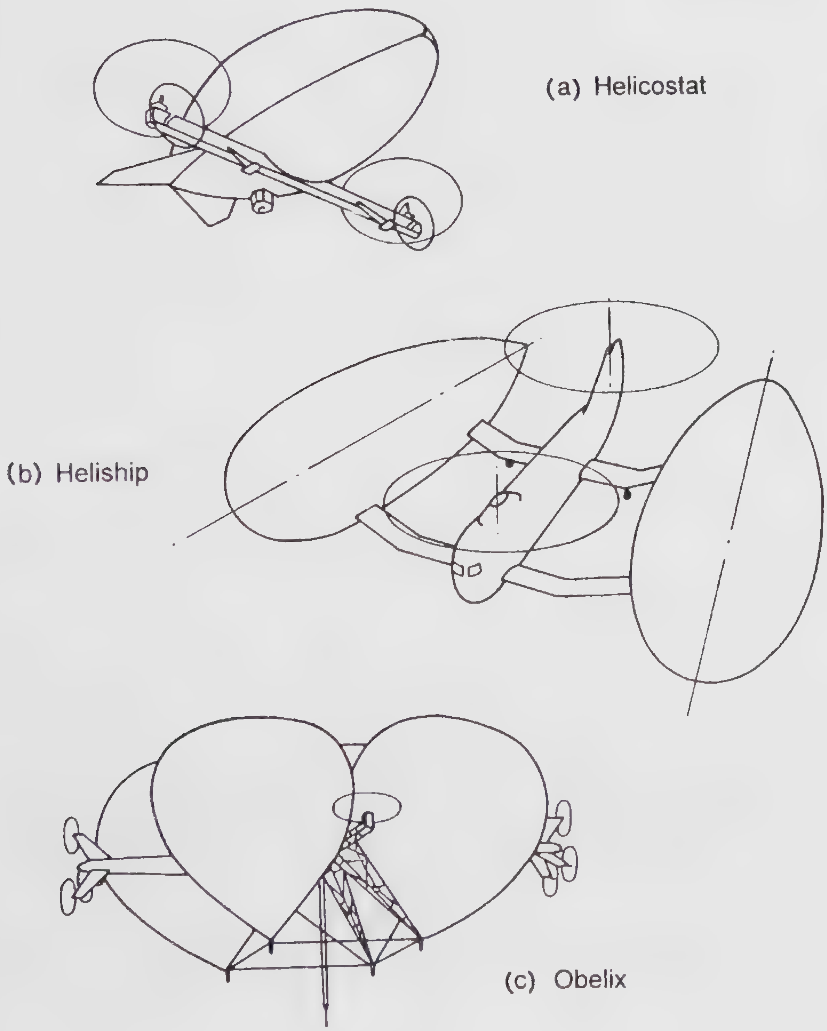


Figure 15.12. Helicostat, Heliship, and Obelix 2-rotor rotastats (Mowforth, 1991).

The Heliship model could only be controlled in test flight with its axis aligned to the wind direction. Although the Heliship design solves the rotor interlinking problem of the Helicostat, it faces problems in turbulence because, to allow space for the cut-down rotors, the hull centres were placed 40m apart compared with a full hull length of 70m.

A 'flying Crane' concept called *Obelix* comprising four balloons attached to a cruciform frame carrying propulsion units was proposed in 1974 by a French consortium headed by Aerospatiale intended for short-distance movement of large indivisible loads (Balaskovic, 1975). Obelix, with six fixed axes rotors for horizontal thrust and two vectoring rotors for control, may not have been a true rotastat.

Cheeseman and Taylor (1991) propose a 'marriage' between the helicopter (with its better control and empty weight fraction) and the airship (with its relatively cheap envelope and helium) in a *SLAB* (Static Lifting Aerodynamic Body) configuration (Figure 15.13). The *SLAB* is essentially a semi-rigid airship in which the lifting gas is contained in an envelope shaped as a thick symmetrical aerofoil disposed vertically. The envelope shape is a compromise between the structurally efficient balloon shape and a streamlined aerofoil. The *SLAB* occupies about half the horizontal space required by a conventional 'cigar' airship of the same volume. The authors propose three possible combinations of rotors and *SLAB*: (a) Helicopter plus *SLAB*. (b) Tilt rotor tug plus slab, and (c) *SLAB* with integral prime mover. The *SLAB* has no aerodynamic controls since the power provides rapid and precise control in all flight regimes. The authors conclude that this design is cheaper than a large helicopter or dedicated airship.

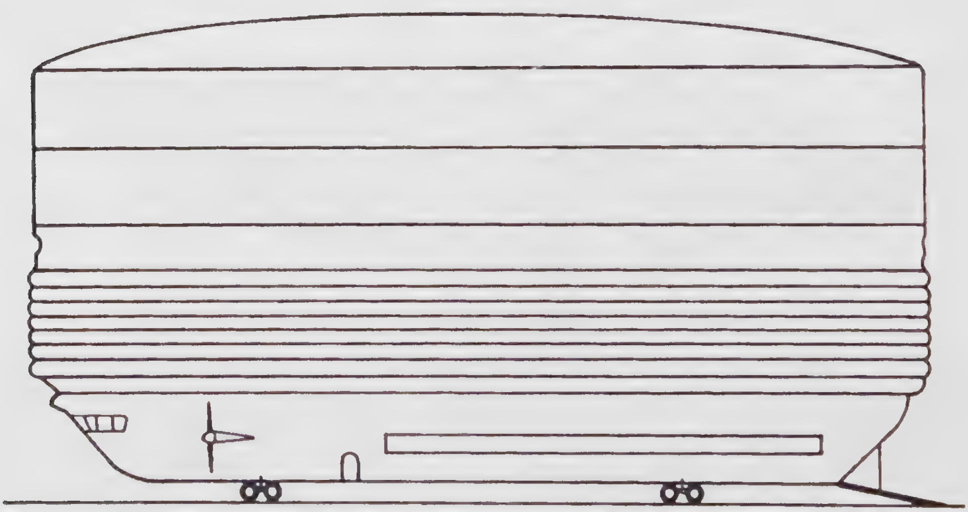


Figure 15.13. Twin rotor SLAB airship (Cheeseman & Taylor, 1975).

Single Rotor Toroidal designs (Figure 15.14) for vertical thrust are usually proposed for housing inside the ring of a torus-shaped hybrid airship as in the Canadian *Toroidal Balloon Concept* (Todd, 1986) and the Japanese *Toroidal Semi-Buoyant Station* (Tachibana *et. al.*, 1991, 1993).

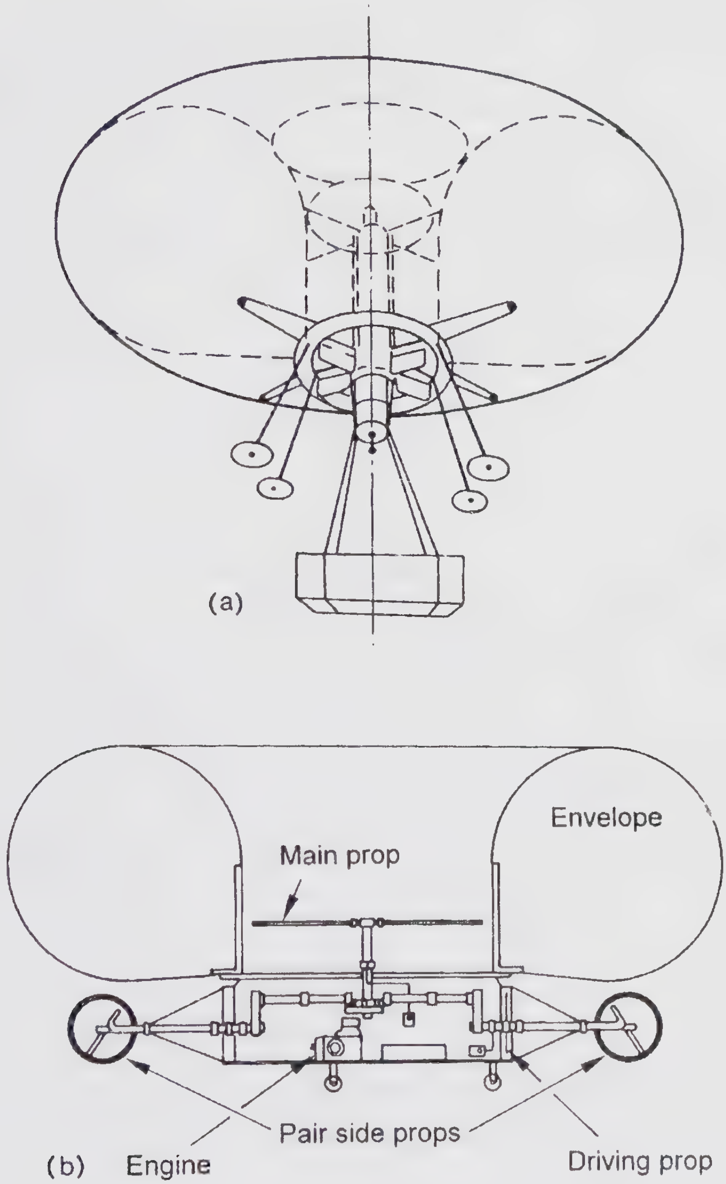


Figure 15.14. Torridal 1-rotor airship designs.

Rotating Hulls (Aerocrane, Cyclocrane, Magnus Aerolift)

Powered payload lift may also be provided by rotating hulls of different configurations utilising imaginative combinations of propellers, aerodynamic surfaces, and the Magnus lift effect.

The *Aerocrane* concept (Figure 15.15) was first proposed in 1974 by the All American Engineering Corporation for short-distance lifts (Airship, Sept. 1987). Aerocrane comprises a spherical balloon fitted with four variable-incidence radial wings each carrying its own propeller turbine. The whole assembly (except for the control car and slung payload) revolves about a vertical axis. The load, slung beneath the non-rotating car, is lifted by varying the wing pitch. A wide range of vertical lift is thus produced. Lateral motion is achieved by tip fins with cyclic control. However, in flight control of a model with an overall diameter of 12.2m was not successfully achieved because of complex interactions between aerodynamic and gyroscopic effects.

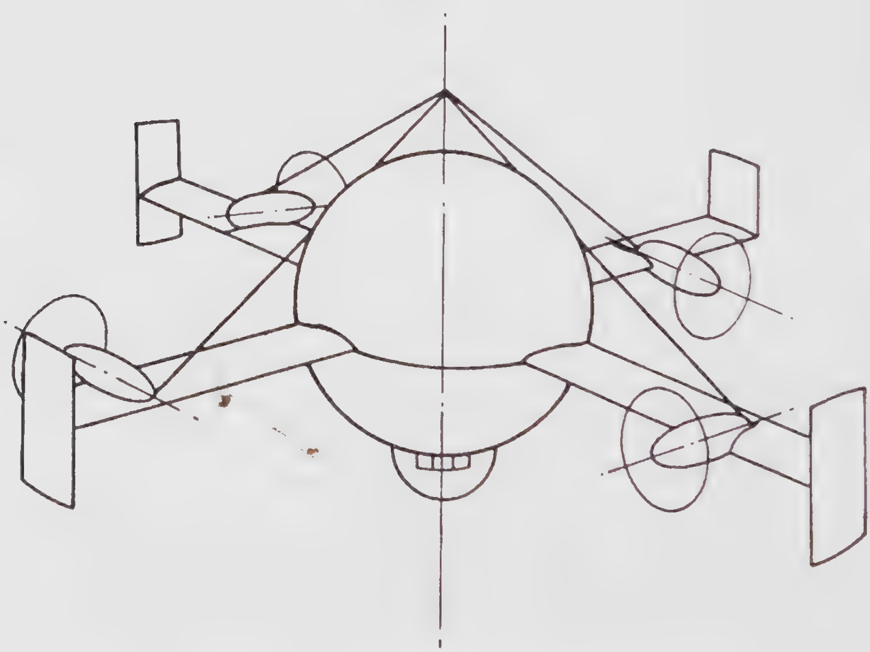


Figure 15.15. Aerocrane rotating hybrid airship.

An equally complex, but more successful, was the *Cyclo-Crane* proposed by Aerolift Inc. in the 1980s (Figure 15.16). Cyclo-Crane comprises a winged 'ellipsoidal' aerostatic hull rotating about its central horizontal axis at 13 rpm during hover (Curtiss, 1981) (Jensen, 1982) (Crimmins, 1985) (Morris, 1985). Dynamic and rotor lift are provided by four variable pitch radial wings located amidships carrying variable pitch end plate aerofoils forming T-shaped units. Two of the wings tips carry engines and propellers. The non-rotating control car and payload are slung on cables from bearings located at nose and tail on the airship's central axis.

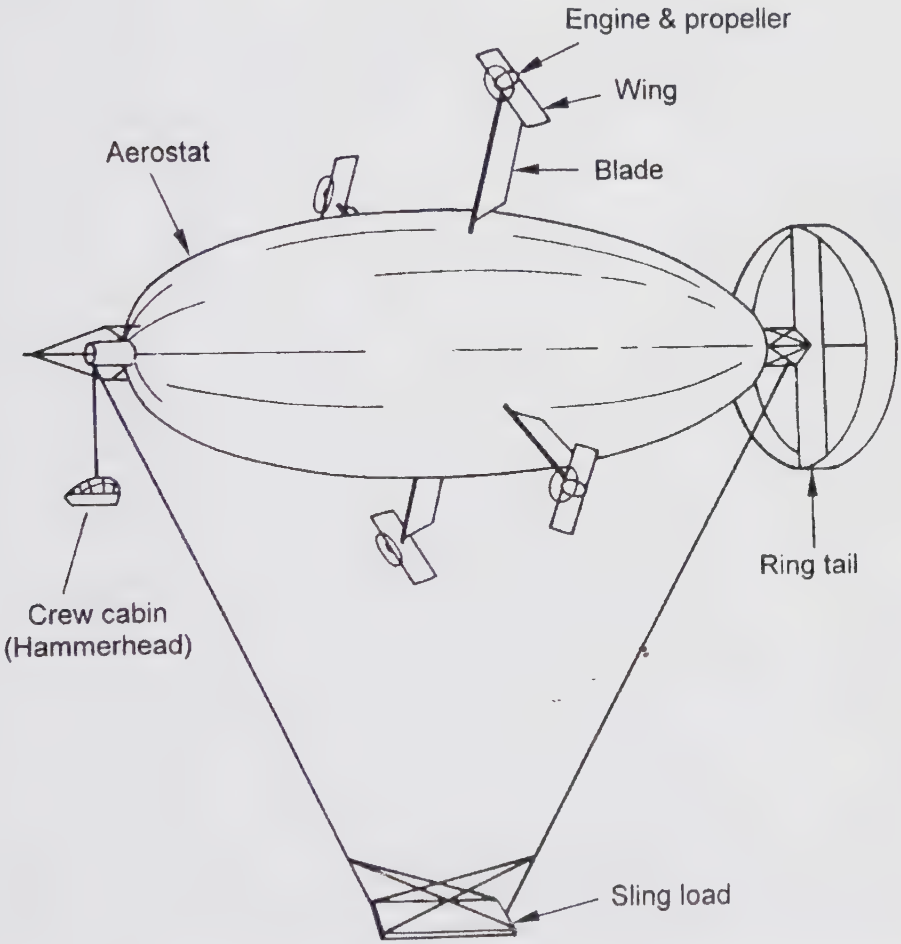


Figure 15.16. Aerolift's Cyclo-Crane.

The hull ceases to rotate during cruise, and dynamic lift is maintained by whichever pair of wings and endplates are horizontal (Figure 15.17). A small (hull: length 42m, volume 9,340m^3) 'demonstrator' capable of carrying a two-man crew and a slingload of 2 tonne was successfully flown in 1984. Including the slung car, the Cyclo-Crane was 79m high. A top speed of 64 km/h could be achieved with the two 112 kW piston engines.

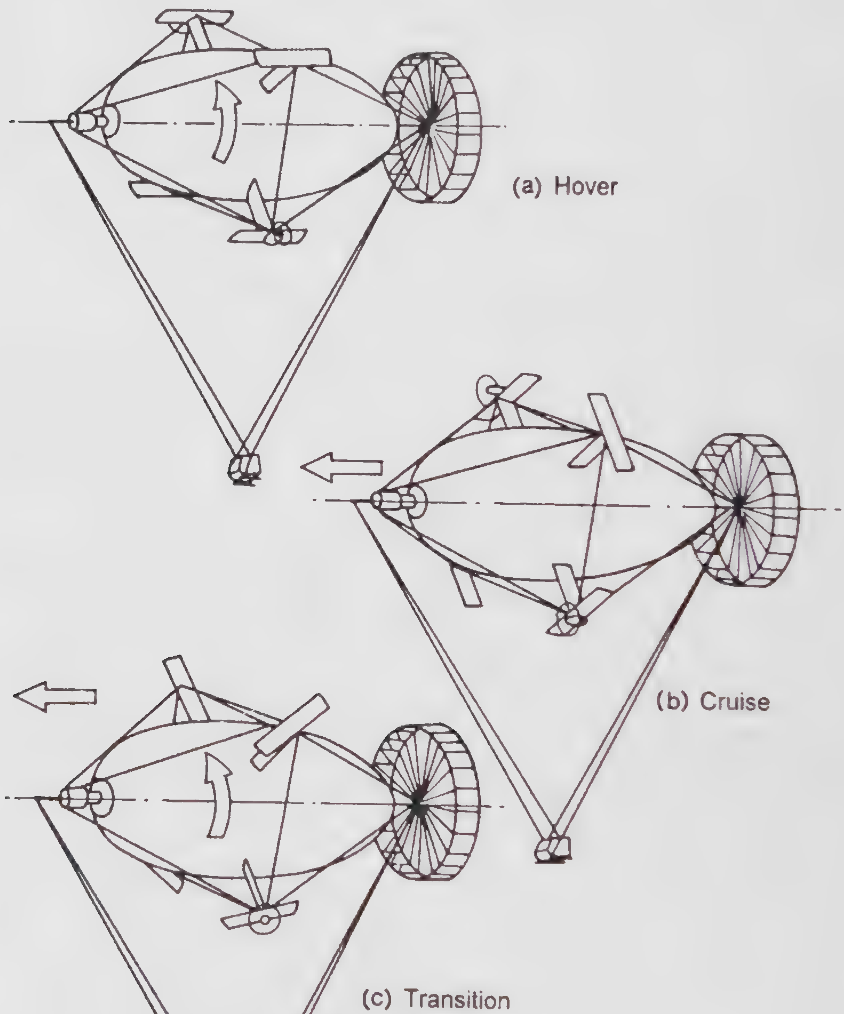


Figure 15.17. Flight modes of the Cyclo-Crane (Morris, 1985).

The *Magnus Aerolift* spherical airship (Figure 15.18) utilises a different principle from that of both the Aerocrane and Cyclocrane to provide the additional dynamic lift. It is based on the phenomenon observed in a spinning golf ball where the rotation of a sphere in an airstream generates a 'Magnus lift' effect.

Figure 15.18. LTA 20-1 spherical rotating airship model in test flight.

The *LTA 20-1* Magnus Aerolift airship (DeLaurier *et. al*, 1982, 1983, 1986) comprises a gas-filled sphere revolving around a horizontal axis at right angles to the direction of flight (Figure 15.19) and carrying load through a yoke suspended from this axis of rotation. Two engines were used both to turn the sphere and to provide vectored thrust when necessary, as when the vehicle was unable to generate Magnus lift during hovering in still air. An unmanned small (6m diameter sphere) demonstration model was flown in 1981 powered by two 1.1 kW electric motors providing a total lift of 96 kg allowing a payload of 15 kg. The proportion of lift provided by the Magnus effect in a full-scale prototype (49m sphere, 59,500m^3 volume) flying at 92 km/h would have been 13 tonnes compared with 63 tonnes of aerostatic lift, or 17% of the total lift (Magnus plus static). The fuel consumption of a 61m model cruising at 135 km/h and carrying a 50 tonne payload would have been very high at 11 tonne/hour (1.63 kg/capacity tonne-km). Another problem relates to the vertical separation of the thrust line from the centre of gravity resulting in oscillations of the suspended accommodation during changes in thrust. Also the Magnus effect would translate axial gusting into vertical lift fluctuations (Mowforth, 1991).

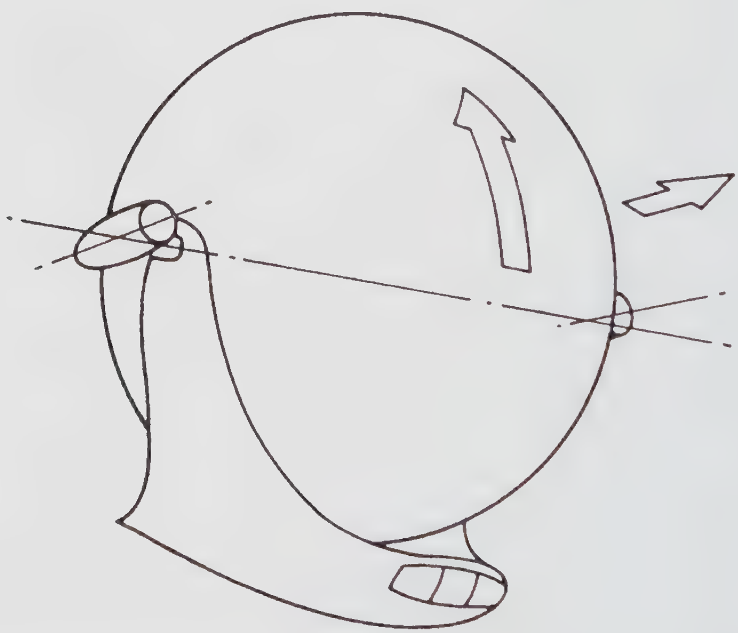


Figure 15.19. Sphere rotation and engine swivel in LTA 20-1.

POWER SOURCE

The drag of a 'pure' airship is approximately proportional to the square of the velocity. Hence it may be concluded that the best cruise speed will not be high. In fact, most design studies, as well as actual craft, have operating speeds of less than 40 m/s (144 km/h). Non-cruise applications (e.g. advertising) may require significantly less speed. This relatively low power requirement makes it possible for airships to utilise low power sources such as solar energy combined with electric motors, albeit supplemented by on-board energy storage.

Electrical

Although the internal combustion engine operated by petroleum fuels has provided the power in conventional airships, it is interesting to note that the first 'successful' airship *La France*, flown in 1884, employed a 7 kW electrical motor and 460 kg of batteries to achieve a speed of 20 km/h and an endurance of four hours.

The problem with electrical power has since then been the low energy-to-weight ratio of the storage batteries. The merits of using batteries, fuel cells or flywheels are considered in Chapter 16.

Solar

Solar energy is a spatially distributed, and not concentrated, source of energy. At peak conditions, about 1,000 kW/m^2 of solar energy is received at sea level. However, because of the airship's inherently large surface area, and its relatively low power requirement, significant speeds can be achieved from solar power alone in sunny climates. Assuming propulsion is achieved via electrical conversion of solar energy, a major factor determining the amount of power available is the conversion efficiency of the 'solar cells' (see Chapter 16). A solar-powered airship is defined as an airship that attains its power for propulsion primarily from solar energy, albeit in conjunction with on-board energy storage for operations at night and in windy conditions. An outline of this '*Sunship*', first proposed by the author in 1972, is shown in Figure 15.20 with more details given in Chapter 16. Solar energy could also be used in other types of airship to provide a supplementary source of energy.

Solar energy is attractive in an environmentally conscious age. Sunlight is a renewable, 'free', non-polluting and non-inflammable fuel. A solar-powered airship would not require re-fuelling when operating in remote sunny areas of the world or at high altitudes, thereby achieving long endurance. Furthermore, a solar-powered airship is a constant weight vehicle, and trimming problems associated with weight loss on fuel consumption do not arise.

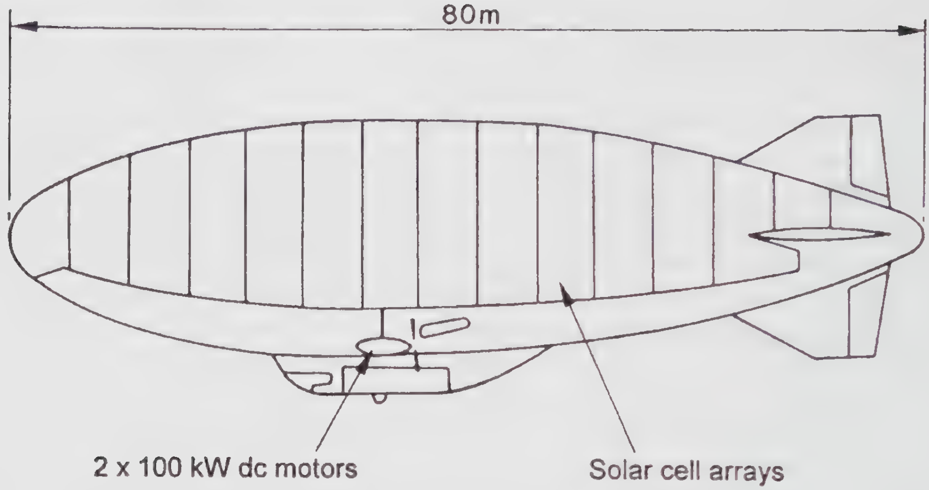


Figure 15.20. Outline of the Sunship concept (Khoury and Mowforth, 1978a&b).

Max length	16	m	Area of solar generator	7.02	m^2
Max diameter	4	m	Peak output	1123	W
Volume	109	m^3	Battery capacity	1080	Wh
Max power	1500	W			
max speed	46	km/h			
Max climb rate	10	m/sec			

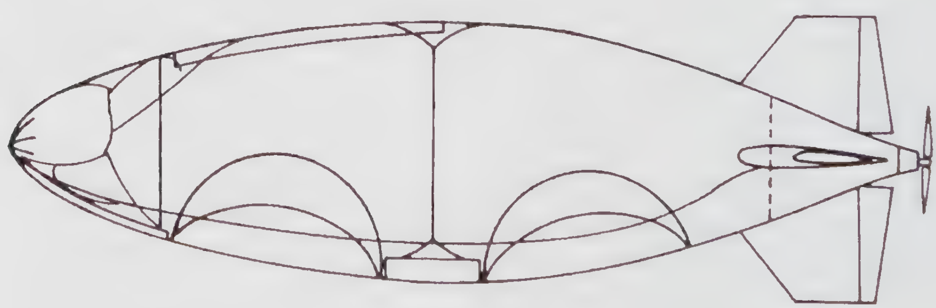


Figure 15.21. LOTTE solar cell powered airship (Remet *et. al.*, 1995).

It is not surprising, therefore, that this subject has received much attention both for low altitude applications (Khoury and Mowforth, 1978a&b) (Khoury, 1986), (Knaupp and Schafer, 1993) (Kampf, 1993) (Schafer, 1993) (Rehmet and Knaupp, 1993) (Rehmet, 1994) (Remet *et. al.*, 1995) (Kroplin and Schafer, 1995) (Gasbag, 1996) and for high altitude applications (Ward and Taluy, 1991) (Onda, 1992) (Onda, and Morikawa, 1992) (Air & Cosmos, 1993) (Ford and Onda, 1996).

Example calculations (Khoury 1986) - for a *Sunship* 80m long (hull volume of 22,000 m^3) flying in cloud free conditions in the tropics at solar noon - show that the hull can receive a total (direct, reflected and diffused) solar energy of 2,614 kW. In conventional airship design, this considerable amount of energy is reflected away by the use of a white or silver coating to avoid superheating. Considering a solar cell conversion efficiency of 15% and a corresponding total efficiency (including electrical and propulsive) of 7.9%, the maximum available propulsive power becomes 205 kW. The corresponding airship speed will be a respectable 101 km/h as shown in Chapter 16.

The power-speed relation for an airship is such that the speed of the Sunship becomes a damped response to variations in solar power input (Chapter 16) which result from changes in orientation of the Sunship during flight and movement of the sun in the sky with time of day or season (Khoury and Mowforth 1978). Further details are given in Chapter 16 which is dedicated to the solar-powered airship.

Two solar-powered radio controlled test models were designed by Michael Walden of LTAS Inc. in 1978-9 and flown in the Nevada desert (Airship, no. 56, June 1982). His later version would have been a spherical 24m diameter model (Airship, no. 63, March 1984).

A 7m long '*Solar Egg*' drone was built by the Tokyo-Sanyo Co. Ltd. of the USA. It employed amorphous silicon solar cells having a power/weight ratio of 200 mW/g. Carrying a camera, the unmanned model airship flew in 1992 at 10 km/h (Airship, no. 99, March 1993).

At the time of publication, a series of three prototype radio controlled solar-powered airships designated *LOTTE* (Figure 15.21) were built and flown since work on them was started in 1991 by Michael Rehmet at Stuttgart University. The first model *LOTTE-1* was flown in April 1993 but was destroyed in June in its hangar in a thunderstorm. It was reconstructed with minor changes to become *LOTTE-2* which took part in the World Solar Challenge in Australia in November 1993, where it flew for about 330 km within four days but crashed into a tree after its radio control system interfered with the ILS-localiser of a military airport. *LOTTE-3* was similarly constructed as the earlier models but with an advanced radio control with two frequencies in parallel, and in-flight data acquisition telemetry system (Rehmet *et. al.*, 1994, 1995). It was 15.6 m long, 109 m^3 envelope volume, with a payload of up to 20 kg. *LOTTE-3* could achieve a maximum airspeed of 45 km/h employing silicon solar cells with 15% efficiency with a total active area of 6 x 1.17 m^2. Because of the other losses in the system, the available propulsive energy was reduced to 10% of the incident direct solar irradiation. The electric motor power was 800W (Short-term 1.5 kW) operating at 4,000 rpm reduced to 800 rpm propeller speed. Ni/Cad batteries (6 x 4.5 kg) with a maximum energy capacity of 6 x 180 Wh were used.

The Pan Atlantic Aerospace Corporation from Canada has proposed a Long Endurance Manned Solar (*L.E.M.S.*) airship (43 m long, 6.7 m diameter) with solar cells mounted on the upper surface (Airship, no. 105, September 1994).

Solar power has also been proposed for high altitude unmanned airships operating at an altitude of 20 km. A five year programme in Japan by Masahiko Onda (Figure 15.22) culminated with the flight of a 20 m long, 181 m^3, solar-powered radio controlled *HALROP-20* using 36 solar cell panels and a nickel-zinc battery (Airship, no. 100, June 1993). During the day, the full-scale *HALROP* (> 200 m long, total buoyancy 20 tons) will obtain propulsion power from solar cells placed on the hull`s top surface and store part of the electricity in costly regenerative fuel cells (5 tons) for use at night. With high efficiency solar cells covering 15% of the hull`s surface, the authors state that it could achieve the 112 km/h speed required to counter wind currents and enable it to stay at a fixed point above Tokyo (Onda 1992, Ford and Onda 1996).

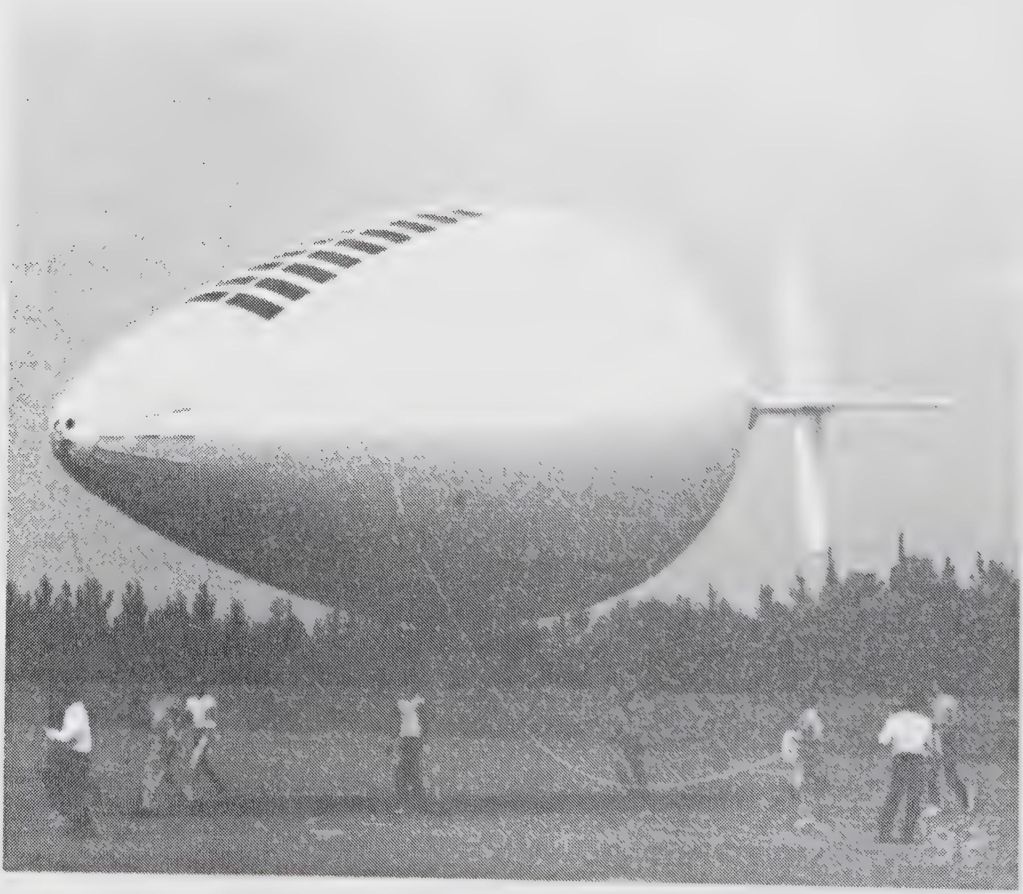


Figure 15.22. Solar powered high altitude airship (Onda, 1996).

Human

The first 'successful' controlled human-powered flight was probably made by C.F. Ritchel in 1878 who achieved a still air speed of about 5.6 km/h (Jackson, 1971). Before that date, attempts were made by both Hugh Bell in the UK (1850) in a 2.4 m airship, and Dupuy de Lome in France (1872) in a 5.7 m airship powered by eight sailors.

In recent times, human-powered airships were built by three groups (Table 15.2).

Watson's *White dwarf* (USA) was 14.6 m long and had an envelope volume of 176 m^3. It achieved a human-powered speed of 13 km/h (Allen, 1988).

Geiser's *Zeppy I* (France) was 12.5 m long, had a volume of 115 m^3 and an empty weight of only 25 kg. A human-powered cruise speed of 15 km/h (maximum nearly 25 km/hr) was achieved (Airship, no. 88, June 1990). The larger *Zeppy II* (Figure 15.23) was to be operated by two pedallers at a cruise speed of 20-25 km/h (higher in the wind direction). It was 20 m long, had a combined helium-air volume of 600 m^3 and a total weight of 85 kg. Extra strength was provided by a tubular keel of carbon fibre. Lightweight solar cells provided electricity for radio communications as well as power through a 300 W electrical motor to the ballonet and water pump. Trial flights were made in 1992 but the trans-Atlantic attempt in 1993 was aborted when the airship was driven into the sea by a gust of wind. The pilots Feldzer and Hulot were quickly rescued by an escorting ship (Airship, no. 100, June 1993).

Dorrington's '*D*' series (UK) were built with the assistance of students at Southampton University. Airship '*D2-bis*' was 20.2 m long with an envelope capacity of 218 m^3. It achieved 5.5 nautical miles and a speed of about 10 km/h on a return crossing of the Solent estuary in 1992. '*D3*', called *Spirit of the Forest*, was 21 m long and had a helium capacity of 266 m^3 capable of carrying one pilot, equipment, and lead-acid batteries for intermittent auxiliary vectored thrust. It achieved a maximum flight altitude of 26 m and a human power speed of 12 km/h, which increased to 19 km/h with the aid of electrical power (Dorrington 1993). '*D3*' was used in Sumatra as a camera platform above the forest canopy. In 1995, a 400m^3 airship was flown in Sabah, Malaysia, powered by human and/or (solely) by electric power.

Dorrington published a list of eight important safety considerations for human-powered airship flight. These include comprehensive test flights in internal space; inclusion of a high venting rate helium relief valve; capability of thrusting down at a vertical speed of at least 1 m/s in thermals; accurate monitoring of weather conditions; inclusion of safety equipment (life jacket, rope and harness); inclusion of a licensed transceiver, altimeter and variometer. The airship should also be stressed to a safety factor of at least 5, based on the worse expected dynamic loading situation. Flight permission and licensing issues should also be addressed with the appropriate aviation authorities (Dorrington 1993).

Table 15.2. *Characteristics of human-powered airships*

Designer	Airship	Length (m)	Volume (m^3)	Prop. Dia (m)	Speed (km/h)
Watson	White Dwarf	14.6	176	1.63	13
Geiser	Zeppy 1	12.5	115	2 x 3.0	15
	Zeppy 2	20	600	2 x 4.6	20-25
Dorrington	D2-bis	20.2	218	2.2-2.6	10-11
	D3	21.0	266	2.2	11-13

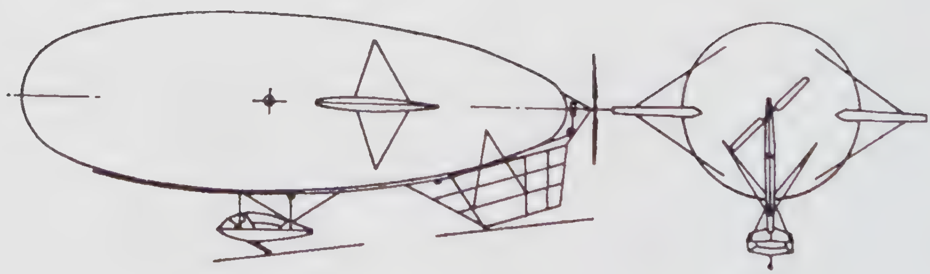


Figure 15.23. Zeppy II human powered airship (Airship, June 1993).

Microwave

Microwave energy has so far been considered as a power source in airships exclusively for high altitude applications. In principle, adequate microwave power can be delivered to maintain an airship on station. The main uncertainties are related to cost and to whether the airship could be blown out of the microwave beam if the wind exceeds the maximum design velocity for any significant period of time. The airship has a distinct advantage over the high altitude unmanned aeroplane for this type of application in that its efficiency in receiving microwave power is much higher because a larger rectenna can be used.

In Japan, Onda has developed in the 1990s a high-altitude unmanned airship (*HALROP*) powered by a 10 kW (maximum) microwave beam transmitted from the ground by a 3 m diameter parabolic antenna with a focal length of 0.75 m (Figures 15.24-15.26). The 3 m^2 rectenna, mounted on the outer underside of the airship, has a power output of 5 kW and is constructed of a lightweight honeycomb sandwich of less than 16 mm thick. Since the power received by the airship may change because of improper tracking or wind interference, a supplementary on-board power source would be installed to supply power for the inverter of the thruster motor (Onda, 1995).

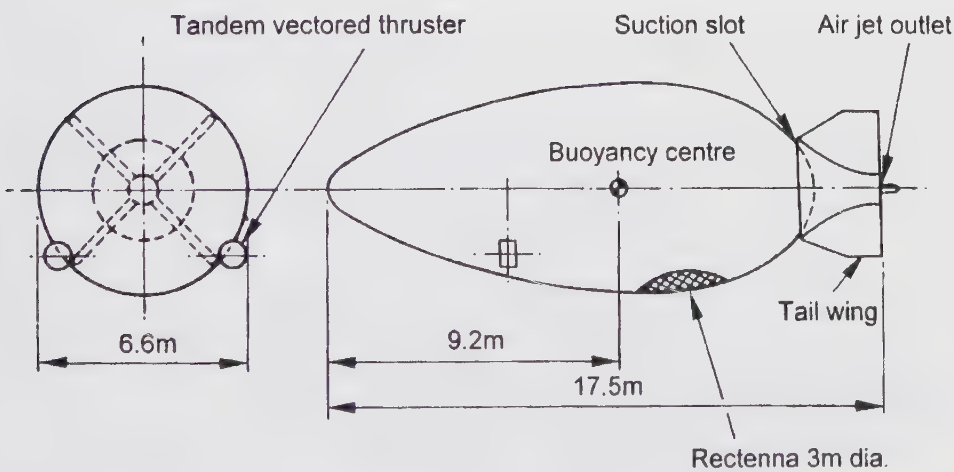


Figure 15.24. Outline of high-altitude microwave-powered airship (Onda, 1995).

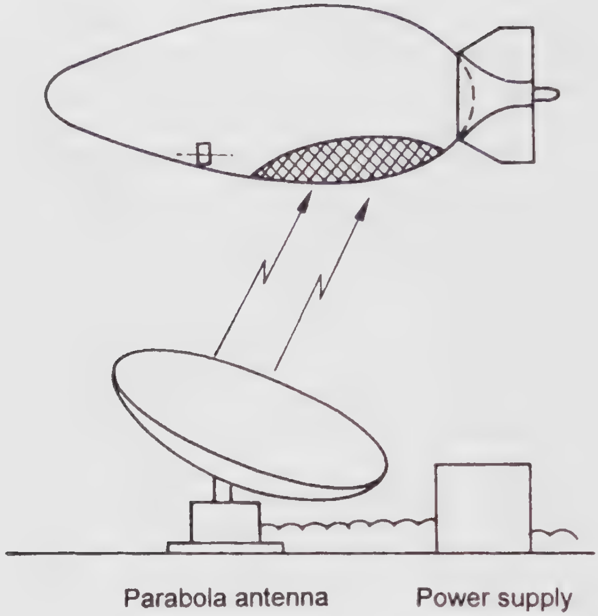


Figure 15.25. Image of a hovering test during microwave transmission (Onda 1995).

Figure 15.26. Photograph of prototype microwave powered airship (Onda 1995).

Hydrogen

Hydrogen fuel is being considered for land vehicles (such as cars and buses) because it produces fewer polluting exhaust emissions. It is also advocated as an answer to a potential petroleum fuel shortage. According to EURO II standards, a hydrogen-fuelled engine produces 90% less nitrogen oxide and nearly 100% less CO and hydrocarbons than an equivalent petrol or diesel fuelled engine.

The use of hydrogen in airships is precluded on the basis of past experience. Despite this, there has been a number of advocates (Decker, 1976) (Bredt, 1985) for the use of hydrogen as fuel in airships, and even as a lifting gas.

Howe (1971) proposed the use of a hydrogen cell based within the helium cells of a 1000 ton rigid craft. The hydrogen was burnt in an auxiliary engine to compensate for the weight loss due to the use of diesel fuel for the main powerplants. The hydrogen itself, however, did not provide enough energy to propel the craft.

Funded by the US Navy, Lockheed put forward a design for a high-altitude (21 km) long-endurance surveillance airship fuelled by hydrogen engines (Airship, no. 57, September 1982).

Bredt (1985), President of the Buz Airship Co., New Orleans, suggests that, on the basis of cost, there is a need to rethink about using hydrogen, both as a lifting gas and a fuel source, using modern lightweight fire retardent materials into a rigid frame for adequate fire protection. Hydrogen drawn from the gas cells into the engines would aid buoyancy control.

Nuclear

Nuclear powered airships have been proposed by more than one designer (e.g. Morse in the USA in 1966 and von Veress in Austria in the early 1970s). Morse (1966) proposed a traditional rigid airship (299m long, 357,000m^3 gas capacity, cruise speed 150km/h) powered by a 55 tonne pressurised water reactor placed amidships and providing a power output of 4.5 MW. Apart from the technological problems associated with such a design, the environmental issue has precluded their practical consideration.

STRUCTURAL CONFIGURATION

Variations in structural design (e.g. rigid, semi-rigid, and non-rigid) were more common before World War II than in the second half of the twentieth century when the non-rigid design has been the predominant structural configuration. It appears that about 850 non-rigid airships were built between 1900 and 1970, about 162 rigid airships were built between 1900 and 1940 (Mowforth, 1991), and about 70 semi-rigid airships were built in Italy, and a few in other countries, between the two world wars (Blenn, 1992).

Since weight is a critical aspect of structural design, a comparison is made in Figure 15.27 of the percentage of empty weight to gross weight plotted against volume for airships of the three types that have been built in the twentieth century (Reid, 1987). The empty weight includes engines and equipment as well as structure. Contrary to expectation, there does not appear to be a reduction in empty weight with increase in volume showing the benefit of increase in size. Also, there does not appear to be demarcation where one type starts to show an advantage over another. All it indicates is that airships that were strongly built, such as the *R100* and *R101*, had a higher percentage empty weight than those that were proven to be fragile like the *R38* (Reid, 1987). Structural weight, however, remains one of the most critical factors in airship structural design. A target of no more than 30% of the gross lift is needed for the airship to be economically viable (Howe, 1991).

Generally, non-rigid constructions appear to be more suited for smaller airships and rigid constructions more suited for larger airships. The largest non-rigid airships flown (*ZPG-3W*) had a 40 ton lifting capacity. The Sentinel 5000 extends this to about 50 tons.

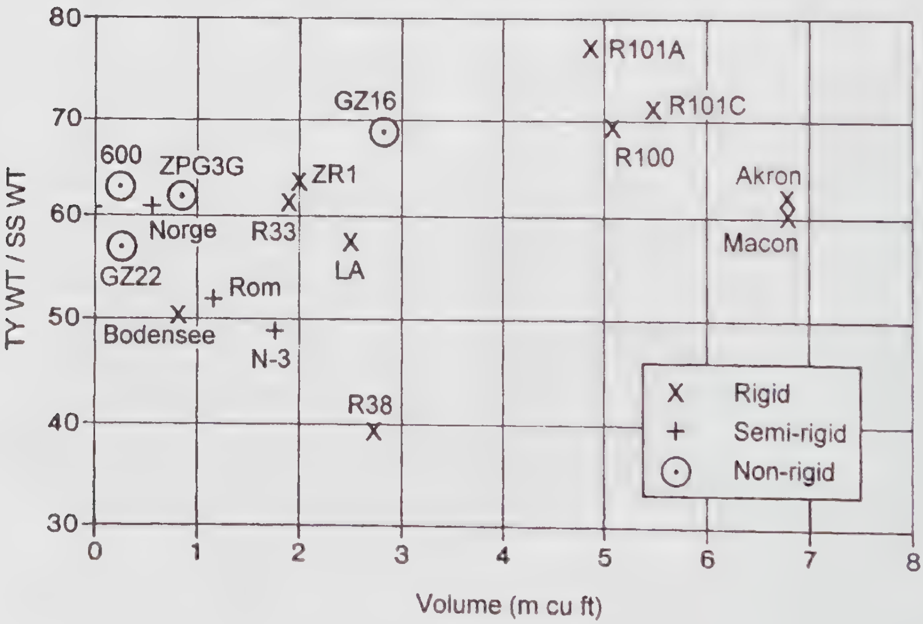


Figure 15.27. Empty weight versus gross weight of airships (Reid, 1987).

The rigid airships built before World War II presented problems in stress analysis of the space framework structure. They were also labour-intensive in design and construction to a degree that is now uneconomical. Recent proposals aim to solve these problems by employing (a) a simpler framework as in the recent *Zeppelin NT* airship (Hagenlocher, 1995), (b) a monocoque shell construction as in the *Gas Transporter* (Munk, 1975), or (c) a metal-clad pressurised airship as in the *R.30* (Airship, no. 57, 1982). Nevertheless, a large (3.5 m ft^3) pressure-rigid structure with a girder framework and metal skin has been proposed for AEW roles (Woodward, 1989). Its author states that the dead-weight would be 5.5% greater than that of a conventional rigid airship.

In a stiff shell design, the skin is stabilised by double curvature at all points. As the airship size increases, the shell curvature decreases so that the skin begins to assume the properties of a thin plate, which becomes unstable and collapses in wrinkles when subjected to compression or shear in its own plane. To prevent this, the skin either must be stiffened to resist wrinkling, or it must be subjected to a biaxial tension field strong enough to overcome any compressive stress that might be imposed by operational loading. The former approach leads to a monocoque system and the latter to the pressurised metal-clad structure as used on the *ZMC-2* airship.

Monocoque Rigid

In many ways the monocoque shell appears to be the most attractive solution for airship structures. Procedures for the accurate and efficient design of stiffened surfaces have been intensively developed for aerospace applications. Since the structure forms a continuous envelope, the gas containment and structural beam functions may be accomplished simultaneously. A further advantage of the stiffened monocoque shell lies in the ability to withstand quite high shear stresses arising from transverse shear and torsion loads without additional weight penalty. Aerodynamic efficiency is improved relative to a flexible outer fabric, and faster speeds could be achieved. The airship shape could also be designed for improved dynamic lift. These considerations have lead to proposals for monocoque designs for large airships such as the *Gas Transporter* (Munk, 1975) and even for small airships such as the Lockheed *Starship* Small Rigid Airship (Gibbens, 1984).

Unfortunately, many of these theoretical advantages could prove to be difficult to realise in practice. Despite the large design bending moments, the endload intensities induced in the shell surface are very small because the structural diameter is also large. This will give low structural efficiency even for an optimum design. Furthermore, the ideal optimum cannot be approached in practice since the detail dimensions required (e.g. skin thickness) prove to be very small, leading to an impractically fragile structure (Richards, 1975).

The rigid monocoque shell consists of a sandwich panel in which two thin metal (or composite) skins are separated by a lightweight core of foil honeycomb (or of plastic foam). The core stabilises the skins so that they can carry adequate levels of compressive, shear and bending stresses without collapse. In an airship as large as the *Gas Transporter* (see below), the sandwich shell would still have to be supported by internal rings and transverse frames, but the structure would remain very much simpler to construct and maintain than the traditional girder-wire-fabric system. However, analysis has shown that the traditional approach, using modern materials, would still weigh less than the monocoque layout, mainly because the stabilising core of the shell adds weight which is not directly load-bearing (Mowforth, 1991). Such considerations have prompted the use of a skeletal structure in the modern *Zeppelin NT* rigid airship (Figures 15.29-15.31). The simplified triangular frame of the Zeppelin NT structure reduces labour and manufacturing costs when compared with the rigid airships of the past. It appears that the structural weight exceeds 40% for some rigid monocoque designs for which figures were available (Richards, 1975), thus exceeding the 30% upper limit for economic viability (Howe, 1991).

'Internal' Monocoque

To overcome the structural weight problem associated with monocoque and metal clad airships, an 'internal' monocoque structure was proposed by Richards in 1975 which reduces the structure weight to below 35% of lift. The idea is to maintain the desirable features of the monocoque design, while avoiding the disadvantages mentioned above.

In this design, the lifting gas is contained within a multi-lobe fabric structure forming the external profile of the vehicle (Figure 15.28). Strength and stiffness are provided by a polygonal monocoque shell enclosed within the fabric envelope. The optimum number of polygon sides was found to be 16. The fabric cover is attached to the vertices of the polygon by a system of radial catenary curtains which are connected to the shell by way of a series of transverse frames located externally on the shell surface. The shell surface itself is constructed from trapezoidally corrugated aluminium sheet, while the transverse frames are braced frameworks. The intrinsically very high structural efficiency of corrugations is fully exploited since the shell surface is not required to be aerodynamic. This feature alone leads to a saving of about 15% of shell weight. The transverse frames are designed to carry transverse shear force increments and radial pressure loads, while at the same time preventing general instability of the shell. An important feature of the design was that it became possible to choose the shell diameter independently of the airship diameter. All these features produce a structure weight at 34% of available lift. A further reduction to 28% is achieved if the aluminium specified for the shell is replaced with composite materials (Richards, 1975).

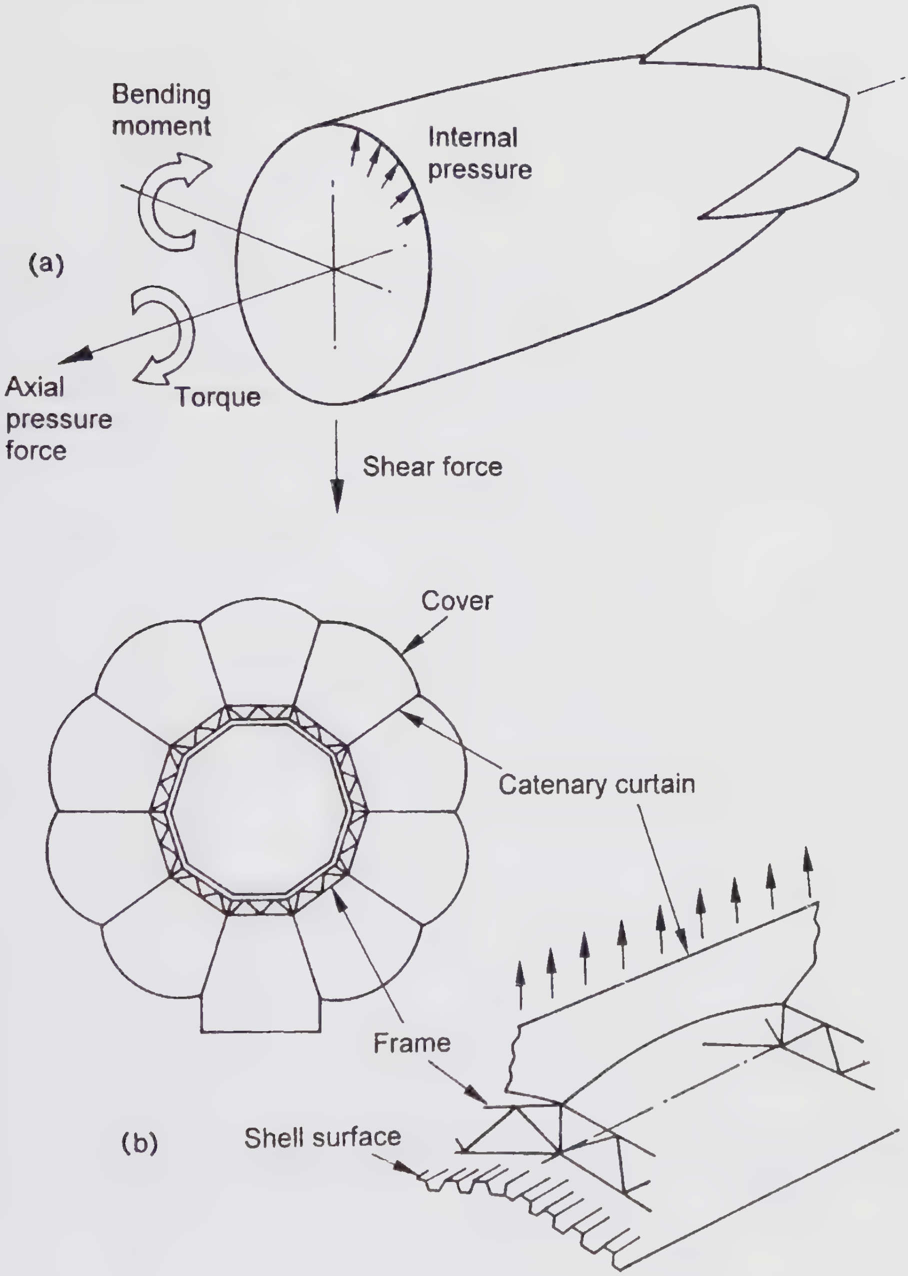


Figure 15.28. Internal monocoque airship details (Richards, 1975).

Metal-Clad

The advantages cited for a metal-clad airship are its simple structure compared to the traditional rigid framework structure and a longer maintenance-free service life than airships employing a textile outer skin. Internal pressure tends to stabilise a thin shell subject to compressive stresses arising from bending moments. Hoop stresses in the shell due to gas pressure are directly proportional to shell diameter, thus, in large airships, internal pressure must be rigorously controlled at a low level if failure from this cause is to be avoided, and no excessive structure weight penalty is to be incurred (Richards, 1975).

The metal-clad concept replaces the textile envelope of the conventional airship by a thin continuous metal skin stabilised by internal pressure. The metal-clad skin thickness is determined by overall bending effects rather than by aerodynamic pressure. It is, therefore, theoretically possible to fly much faster than a conventional non-rigid airship but at a considerable penalty in fuel consumption. Unlike the textile envelope, however, the metal-clad skin cannot be allowed to collapse when depressurised, and some internal structure must therefore be introduced to prevent this. The essential design problem is to establish the lowest practical overall structure weight that will hold the airship in shape without pressure - or during accidental depressurisation in flight. However, a thin metal skin has the ability to recover elastically from a significant degree of local wrinkling so long as yield stresses have not been exceeded. The main design challenge for a metal-clad airship is in the analysis of stress patterns due to loading of a thin shell supported at concentrated junctions by a stiff internal structure, and the accurate prediction of stress concentrations for an adequate variety of loading conditions.

The first metal-clad airship was in fact built by Schwarz in 1897 using a rigid aluminium framework construction covered in aluminium sheet less than 2 mm thick. A pressurised 'non-rigid' metal-clad airship designated the *ZMC-2* was built in 1929 by the Metalclad Airship Corporation (Allen, 1990). The envelope (200,000 ft^3) comprised Alclad panels about 0.24 mm thick made of duralumin faced with aluminium and fitted together by some 3 million copper rivets. To help in stabilising the skin against shear and compression forces, the profile was made with the relatively low length to diameter ratio of 2.93 thus ensuring a degree of double curvature over the whole surface. The *ZMC-2* is claimed to have been operational for 12 years but it has been said that the stubby shape gave a rough ride in unsteady weather. Woodward (1989) proposed a metal-clad airship for AEW missions. For the *ZMC-2* metal-clad airship, the structural weight quoted is in excess of 50% of the gross lift (Richards, 1975), far exceeding the 30% upper limit for economic viability (Howe, 1991).

Semi-Rigid

Semi-rigid airships seek to retain the advantages of the non-rigid concept in larger sizes of airships by combining features of both rigid and non-rigid airships. A pressurised envelope is used at about 30-50% of the pressure of a similar non-rigid.

The frame or keel runs (internally or externally) from nose to stern along the bottom only, and carries the bow frame, fins, gondola, fuel, engines and mechanical components. The keel reinforces the envelope at its weakest point and helps carry and distribute both static and dynamic loads. This allows a lower internal pressure and more freedom in component design and location. The extra weight/cost of the keel is partly offset by savings in fabric weight/cost.

The semi-rigids of the past compare well with the non-rigids and rigids in terms of percentage of empty weight to gross weight as shown in Figure 15.27. Perhaps development along these lines, or extending the gondola of a non-rigid to form a keel, could be a line worth pursuing

A major problem, however, is the detail design, especially of the joints between the flexible and rigid components. For future application of the concept, semi-rigid airships need to be much simpler to design and operate than those of the past.

Recent semi-rigid airship designs proposals from the USA include the *UPship* by Blenn (1992) and the *AEROS-50* by Worldwide Aeros Corporation (Airship, no. 108, June 1995). In Germany, Luftschiffbau Zeppelin GmbH have applied patents for their semi-rigid airship design (UK Patent 2254 833). In Russia, the Design Bureau Automatica have proposed a multi-purpose semi-rigid airship designated *DKBA DP-800* (Airship, no. 105, September 1994).

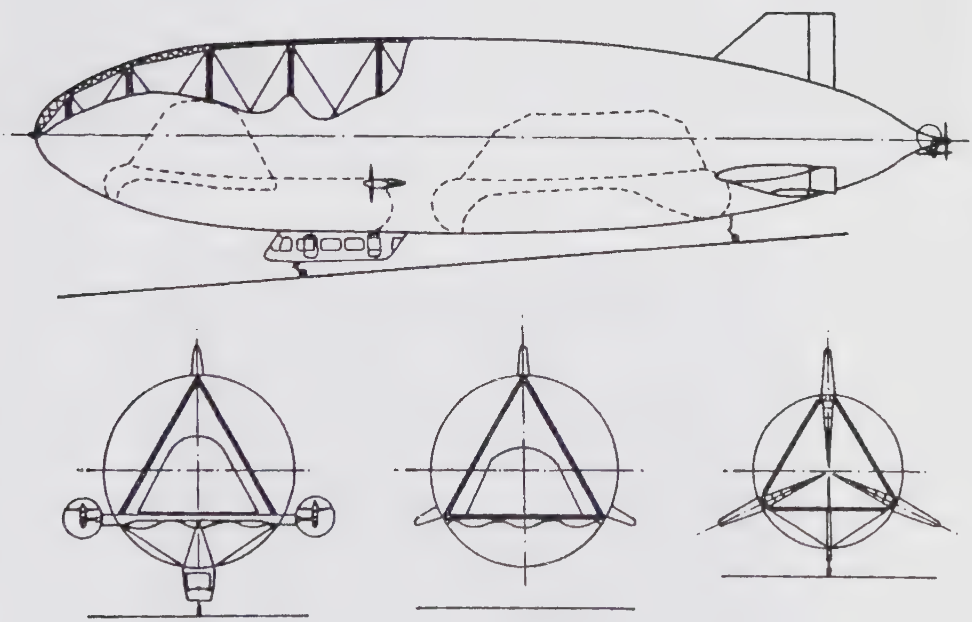


Figure 15.29. Structural outline of the LZ-NT airship (Schlenker *et. al.*, 1993).

Zeppelin NT Structure

The design philosophy of the Zeppelin New Technology (NT) is based on the rigid airframe principle (Figure 15.29). The simple triangular framework (Figure 15.30) allows for cost-effective and low-weight construction. The longerons and frames are made of aluminium alloy and carbon fibre composite materials respectively. The longeron/frame connection points (Figure 15.31) are designed to withstand the specified loads and to facilitate assembly. The LZ N07 is 68.4m long, 14.2 maximum diameter, and with a gas capacity of 7200m^3. At 1000m cruising altitude, the maximum gross weight is 6950kg and the payload 1700kg (Zeppelin GmbH, 1996).

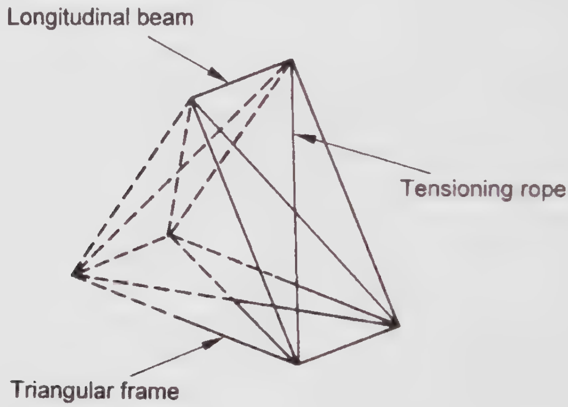


Figure 15.30. Interior structure of the Zeppelin NT rigid airship (Schlenker *et. al.*, 1993).

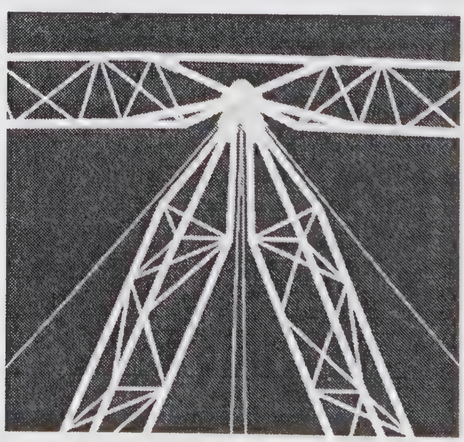


Figure 15.31. Longeron/frame connection points of Zeppelin NT rigid airship (Zeppelin GmbH, 1996).

Pressurised Tube

The concept of a 'rigid' airship constructed of a pressurised tube structure has the attractiveness of flexibility during impact with the structure reverting back to its original shape providing the tubes are not ruptured by sharp objects. The concept has its detractors and needs to be proven operationally, but a remote controlled 7.2 m long '*Airboat*' model with a light pressure tube structure (Figures 15.32-15.33), constructed from 43 independent elements, was flown in 1990 (Bracher, 1996).

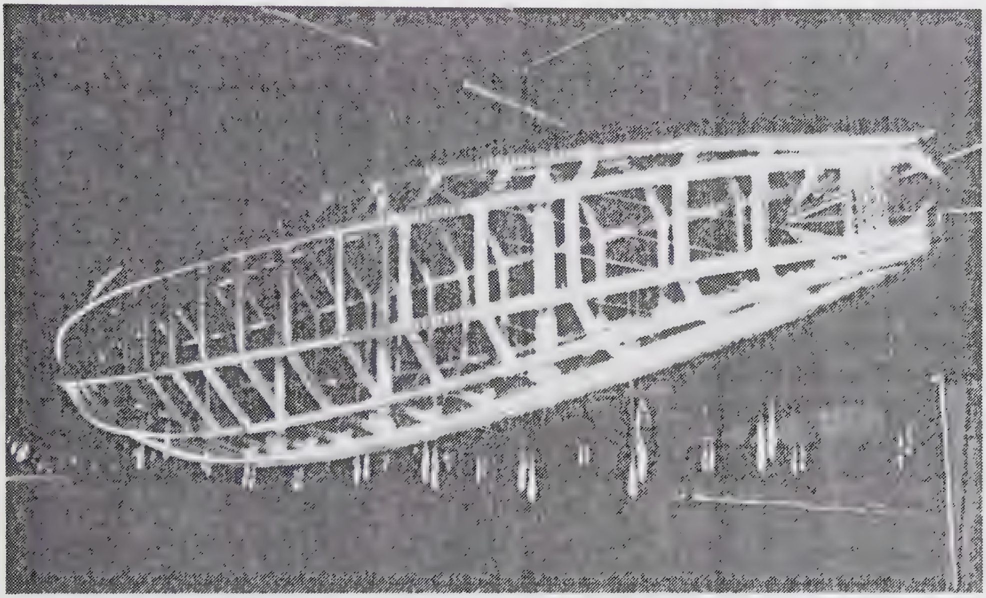


Figure 15.32. The Airboat pressurised tube airship (Bracher, 1996b).

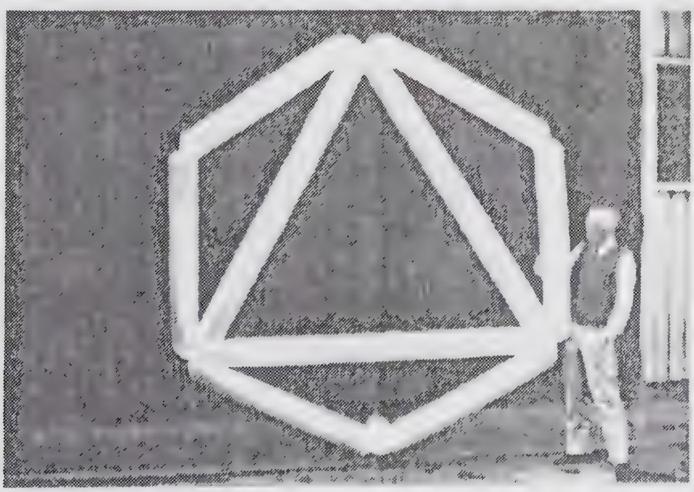


Figure 15.33. An element of the light pressure tube structure (Bracher, 1996a).

The tube material was Nalophan. The tubes were subjected to long-term loading, buckling and fatigue tests at Stuttgart University. They were 10-20 cm in diameter, had a wall thickness of 0.02 mm, and a rupture pressure of 200 kPa.

LIFTING GAS

The lifting gas may be a special gas of inherently low density such as helium (Table 15.3), or it may be heated air which is less dense than ambient air. There are, therefore, two types of airship namely a Gas Airship and a Hot Air airship.

Methane

It is possible to identify two distinct uses of the lifting gas namely, (a) to transport payload as in a conventional airship or (b) to transport gas (e.g. methane) making use of the low density of the gas payload for lifting purposes (Table 15.3).

A large (549m long, 2.75 million m^3 volume) *Methane Gas Transporter* of semi-monocoque design was proposed in the early 1970s prompted by the energy crisis and the high cost of liquefaction plants (Munk, 1975). About 90% of the hull volume would comprise the gaseous cargo and the remainder a permanent helium reservoir to support the 'empty' vehicle on its return journey. Since the gas cargo would itself generate further lift, commercial cargo could also be carried on the delivery leg of the double journey.

Table 15.3. *Characteristics of three four gases*

Gas	Density kg/m^3	Lifting Force N/m^3 (ISA)	Comment
Hydrogen	0.085	11.2	Inflammable, relatively cheap
Helium	0.168	10.2	Inert, relatively expensive
Hot Air	0.906	3.14	Inert, very cheap, relatively poor lift
Methane	0.756	4.5	Inflammable, relatively cheap

Hot-Air

A significant number of small airships have been built since the 1970s with hot-air as the lifting medium, yet hot-air airships are still regarded by some as unconventional. The first recorded deliberate free flight was in 1783 by the Montgolfier Brothers in a 9 m diameter hot air balloon.

Hot-air airships have been used for aerial advertising, sport, and environmental research. The high capital and running costs of helium airships render them cost-effective only if they can achieve a high utilisation. Hot-air airships are by comparison relatively cheap to operate even for only a few hours or a few days. When not in use, they do not incur costs as they could be stored in a trailer without the need of hangarage etc. They also are cheap to transport by road to their place of operation.

Hot-air airships, however, require more volume than helium airships to generate the same lift. By the use of improved fabrics, it may be possible to reduce the weight of the envelope and to operate it at higher temperatures to obtain a greater lift. High temperature materials are being developed for balloons designed for landing on the planet Venus at temperatures of 450°C (Yavrouian, 1995). Hot-air airships can carry only a small payload and flights will primarily cover the local area in the vicinity of the launch site. Passenger transport may, therefore, not be cost effective. Also, hot-air airships are particularly weather-dependent and inflation is only possible in low wind speeds. The *AS 80GD* airship of GEFA-FLUG has been inflated several times in winds of up to 12 knots (Busemeyer, 1994).

There exist two different types of hot-air airships. The first is the so-called 'natural pressure system'. Shape and stability are maintained solely by the static pressure of the hot air in the envelope. This type is relatively simple to build and operate, because many technical features are derived from hot-air balloon technology. The burner unit is positioned under the open belly of the airship envelope. Due to the very low natural static pressure in the envelope, the use of these airships is extremely dependent upon the weather and is virtually restricted to windless conditions. Horizontal manoeuvrability is realised by a side rudder; the rates of climb and descent are dependent upon the burner output. The second type, can be described as the 'fan pressure system' in which pressure is obtained with the help of a fan system positioned under the burner unit. On later models, additional pressure is added with the help of the propeller slipstream. The burner unit now works inside the entirely-closed airship envelope. The pressure is around three times higher than the unpressurised type. Maximum pressure achieved by the mid-1990s was about 20 mm/Wg. The majority of hot-air airships are now of the second type. Volumes vary from 1,500 m^3 for a single seater to 3,000 m^3 for a two seater with some payload. Most of the engines in use are two-stroke varying in power from 20 hp to 60 hp. The resulting speed is about 15 knots. Average flight time varies from one to two hours. Depending on local circumstances, and on the crews' skill, hot-air airships can fly in wind speeds of 5 knots to a maximum of 8 knots.

Cameron Balloons in the UK have built hot-air airships (e.g. *D-96*) since 1972 (Airship, no. 56, June 1982) and, at the beginning of the 1980s, Thunder & Colt Balloons in the UK have produced the first fan pressure hot-air airship (e.g. *G-WZZZ*).

In Germany, GEFA-FLUG has, since the late 1970s, been developing hot-air airships for advertising, environmental research, aerial photography, and archaeological surveys (Busemeyer, 1994). Hot-air airships have also been built in the USA, Argentina, Sweden and China.

In 1988, the first international championships were held, thereby promoting airship technology and pilots' skills.

CONTROL

Most operational airships of the Twentieth Century have been manned. and Chapter 12 is devoted to piloting. There is, however, an increase in the number of unmanned remotely piloted airships (RPAs) being designed:

- for low altitude applications;
- for high altitude applications.
- as test models for full-scale manned airships;

Low Altitude Unmanned Airships

The main advantage of small remotely piloted airships (RPAs) over manned airships is their relatively low procurement and operational costs (Boschma. 1995) (Wells, 1996 - Figure 15.34). Roles for low altitude RPAs include advertising, camera/TV platform, air pollution measurements, and localised surveillance.

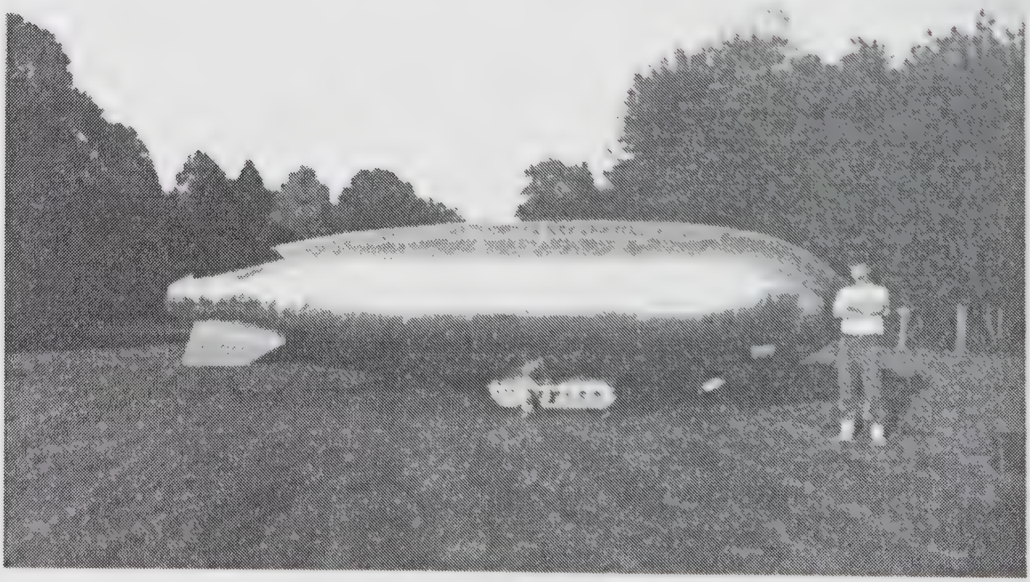


Figure 15.34. Low altitude unmanned airship (Wells, 1996).

Low altitude RPAs have also advantages over competing remotely piloted vehicles (RPVs) - such as radio controlled fixed wing aircraft, helicopters, or tethered balloons. Fixed wing aircraft cannot hover over a target, helicopters tend to have severe vibration problems for camera use and have limited payload, whereas tethered balloons cannot manoeuvre quickly into position. The airship is able to resolve all four problems in one vehicle. Furthermore, in virtually all of its competitors, loss of control or engine failure means that damage to the aircraft, and to the expensive on-board equipment (e.g. camera), is almost guaranteed. In contrast, the RPA is not immediately placed into jeopardy by the loss of one or both of its engines. If subjected to a heavy landing, the shock absorbing nature of the envelope protects the equipment against impact. If power is lost, the RPA will descend slowly being only slightly 'heavy'. Other exclusive safety features include options for a secondary power supply for radio control, secondary controls to land the RPA, and shrouded propellers (Wells, 1995).

There are, however, two main disadvantages of RPAs, transportation and weather limitations. The envelope fabric is prone to damage if repeatedly inflated and deflated. The airship is, therefore, kept inflated for months. This requires a relatively large trailer for road transportation thus restricting envelope size. As for the weather, an RPV such as the *AS-400* (Wells, 1995) is able to operate for only six months in any calendar year in the UK. Turbulence caused by thermal activity can severely hamper operations. Camera tasks can be very difficult to achieve in breezy conditions, although the RPA can fly in winds up to 15 knots or more. The design objectives for an RPA are, therefore, to establish adequate stability and control in bad weather and to simplify ground management.

The US army has developed RPAs in the form of the Small Aerostat Surveillance System, Low Intensity Target Exploitation, airship (Boschma, 1995). In the UK, Nigel Wells has been designing and operating remotely piloted airships since 1981 (Wells, 1985). Kaemf and Well (1995) in Germany are developing an automatic flight management and control system for RPAs incorporating satellite navigation systems like GPS (Global Positioning System) and digital control to achieve high accuracy in following a reference trajectory. Figure 15.35 shows a block diagram of the flight control system. At the heart of this system is the Stability Augmentation System (SAS), which is often combined with low level attitude systems (e.g. altitude and azimuth hold). An outer loop is responsible for flight path control and trajectory tracking.

High Altitude Unmanned Airships

High altitude (e.g. at 20 km) unmanned airships are considered for applications such as surveillance, environmental observations, and telecommunications relays. The requirements for these roles are: (a) to maximise the ground coverage; (b) deliver near-continuous monitoring; (c) operate at mid-latitudes; and (d) minimise operational costs. These lead to the platform having to operate at as high an altitude as possible, stationkeep above the target region, and have long endurance greater than one year. Such requirements preclude the use of manned airships. Compared to satellites, the airship platform in the lower stratosphere has the advantages of being closer to the ground for better resolution images and requires less power for radio wave relay.

High altitude airships (Garnholz, 1995) and tethered aerostats (Ashford, 1995) are also considered as astronomical platforms because the stratosphere is (a) very dry, which minimises atmospheric opacity and radiance; (b) very cold, which minimises telescope thermal emission; and (c) stratified, which hampers the generation of turbulence and associated image blurring effects. In the visible and near infrared part of the spectrum and, to a lesser extent, in the longer infrared and sub-millimetric bands, the resulting conditions approach those of space.

As regards suitable altitudes, operation at an altitude below 5 km is commercially unattractive because the instrument field of view is too small for ground observations, while above 50 km the ambient density is too low to provide sufficient aerostatic lift. A major factor affecting airship design in this regime is the drag power required to stationkeep against the prevailing wind. Minimising stationkeeping velocity is, therefore, a major objective.

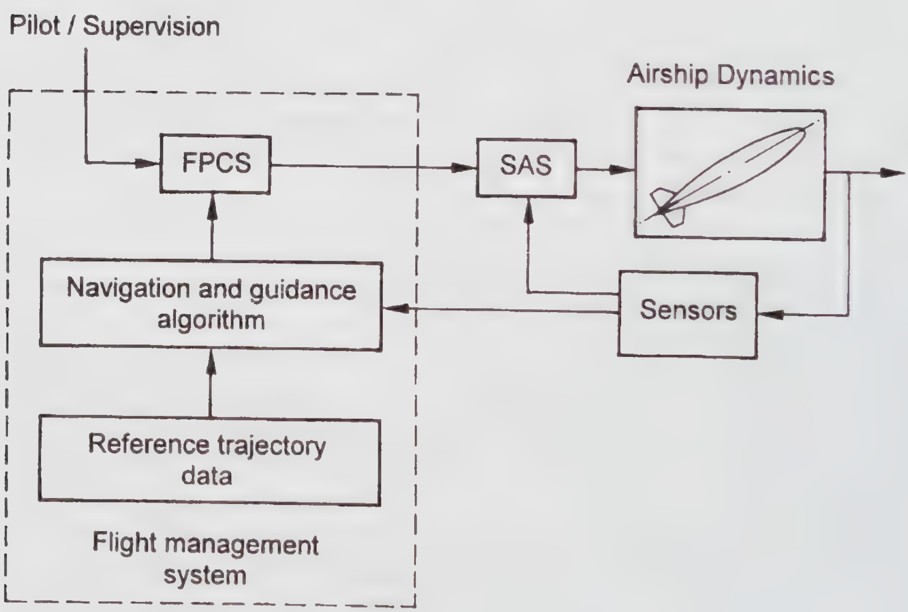


Figure 15.35. Unmanned airship automatic flight control system (Kaempf and Well, 1995).

Examination of global upper atmospheric wind profiles reveals that, at mid-latitudes, the wind speed is a minimum at 17-22 km (Figure 15.36). Hence this altitude range is selected as the operational airship altitude. Further detailed statistical analysis indicates that a stationkeeping speed of 36 m/s (130 km/h) is required to ensure 99% availability throughout all seasons - including winter (Greer, 1993). Although 130 km/h appears to be a high speed, aerodynamically it would correspond to an order of magnitude lower airspeed at sea level since the atmospheric pressure at this altitude is reduced to about 70-40 mb.

As for the aerostatic lift, the fundamental property under the designer's control is the envelope volume. This can be increased to provide any desired lift, but at a penalty of increased envelope mass and hull drag. The atmospheric properties that influence lift, on the other hand, are dependent on the altitude but otherwise cannot be controlled. The airship gas temperature depends on the thermodynamic equilibrium at the envelope skin and is thus passively controlled by the choice of skin surface thermal properties.

It is particularly important in the case of a sealed envelope to choose a material with low solar absorptivity (≤ 0.2) to minimise overpressurisation during the day. The internal pressure must be sufficient to resist wind dimpling and envelope buckling. (2-5% overpressure during worst case conditions).

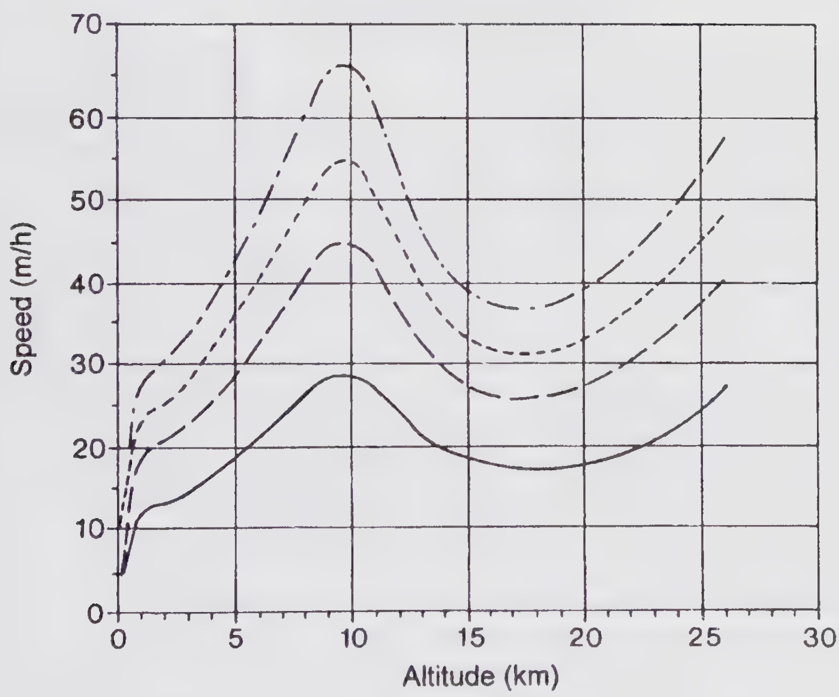


Figure 15.36. UK winter wind speed versus altitude (Greer, 1993).

Minimum internal pressure is obtained by using air ballonets to actively pressurise the envelope which could be made of materials such as aramides (nylon) and polyesters (Dacron). These necessitate an increase of about 10% in the envelope volume, thus increasing drag. Alternatively a sealed envelope made of stronger Kevlar fabric could be used, which maintains sufficient overpressure in night conditions. However, this has the drawback that during the day the internal pressure will significantly increase (due to rising gas temperature) and thus the envelope must be thicker (i.e. heavier) to cope with the increased hoop stress. Helium leakage rates must be less than $5x10^{-5}$ kg/m^2/day to avoid the use of a heavy helium replenishment system. However, the diffusion rates at the high altitudes (20 km, 4 mb), and low temperatures (-60°C), could drop by a substantial factor (Greer, 1993). The required endurance of the airship precludes the use of on-board fuel storage over the length of the mission. Power must instead be supplied throughout the mission. There are two prime candidates for power supply - solar energy or microwave energy beamed from the ground. For the former, a battery or fuel cell system is required to supply power during darkness. Calculations indicate that a regenerative H_2/O_2 fuel system has the better energy/mass ratio. For mid-latitude winter operations the solar cell array must be sized to supply some 28% of its output as direct daytime power, with 72% of the output being used to regenerate the fuel cell (Greer, 1993).

In 1982, the US Navy commissioned Lockheed to study the feasibility of using an unmanned 142,000 m^3 airship for radar surveillance, communications relay, and signal intelligence. Had it been built, the *Hi-Spot* should have been able to hover at 21 km for up to 155 days carrying a payload of 250 kg (Garnholz, 1995).

In the early 1990s, Onda in Japan conceived a High Altitude Long range Observational Platform called *HALROP* (Figure 15.37) comprising a streamlined 'dart' shaped unmanned non-rigid superpressured (5 mb) airship fitted with two tandem thrusters. Its hull is constructed of a lightweight composite material, and the airship uses active boundary layer control to reduce drag. *HALROP* is supplied with power either from solar cells covering 15% of the surface (Onda, 1992) or from a microwave (see above) beamed from the ground (Onda, 1995). In the mid-latitude region in winter, sunlight hours are least and the wind speeds are highest. To meet these conditions, Onda concluded that the airship should be more than 200 m long and should be designed to achieve 31 m/s against the wind currents to enable it to stay at a fixed point above Tokyo with more than 99% certainty. Since helium at sea level inflates by about 15 times when it reaches the 70 mb altitude level, only 10% of the envelope volume is filled with helium gas at the time of launching, and the rest is air. The total buoyancy of the *HALROP* is about 20 tons which includes 5 tons of expensive regenerative fuel cells to provide 100 kW power for night-time propulsion. The fuel cells, however, would not be required for operations above the Antarctic zone in Summer when sunlight hours are quite long and the wind is light. For this application, the *HALROP* would be smaller (about 100 m long) with a total buoyancy of about 7.6 tons which includes 0.1 tons of solar cells (50% efficient and 50 μm thick) covering about 450 m^2 of its surface (Onda, 1992). *HALROP-20* and -23 have, at the rear part of the envelope a slot for intake of the air boundary layer around the hull, as well as a single staged axial fan as a thruster which may reduce wake resistance and enhance propulsion efficiency of the entire hull.

Greer (1993) in the UK concluded that the most technically attractive design is the balloneted Godschmied configuration with active laminar boundary layer control. The airship has a volume of 480,000 m^3 which is much larger than any current airship but is of a similar size to available scientific balloons. A smaller airship (100,000 m^3) would be required if availability is reduced from 99% in winter to ≤ 95%.

Garnholz (1995) considers the airship to be the only class of vehicle suitable as an astronomical platform in the air. Airships combine dirigibility, stability, endurance, low engine vibration, light fuel consumption, and the ability to lift heavy, out-sized payloads on multiple loading points to high altitudes.

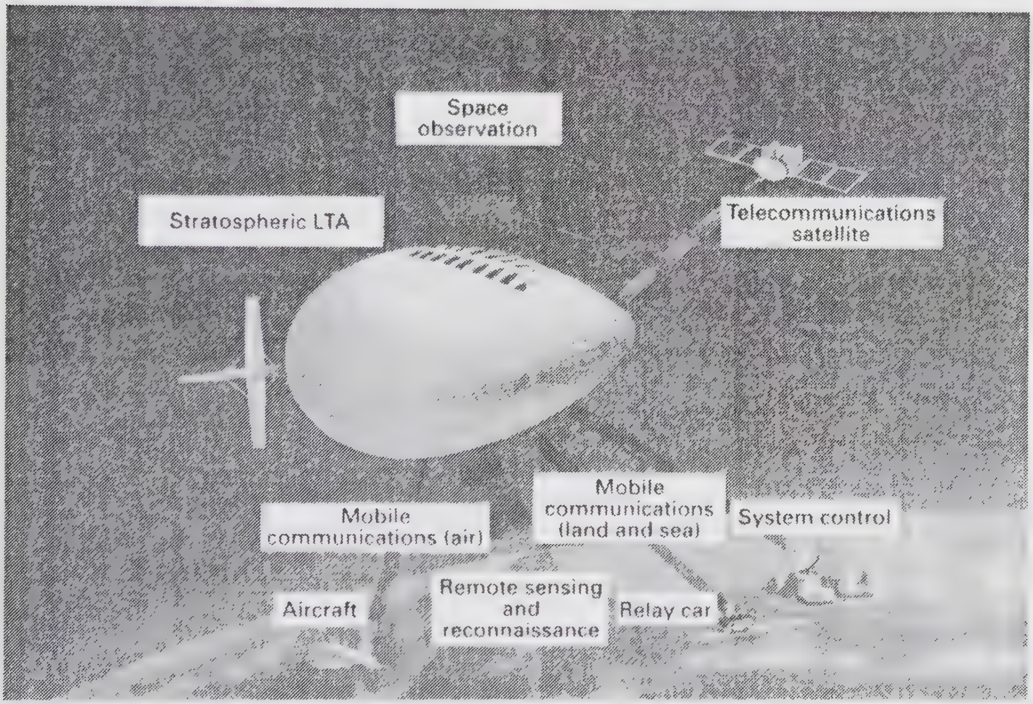


Figure 15.37. HALROP high altitude unmanned airship (Onda, 1996).

PAYLOAD

Heavy loads could be carried by large airships utilising the advantages of the increase in volume relative to surface area, or by smaller size hybrid airships in which the structure is supported aerostatically and the load carried dynamically.

A demand is envisaged for a transporter capable of carrying heavy and/or bulky loads (e.g. heavy turbines, construction elements). The airship has the advantages of being able to provide a point to point transport service, carry large and heavy loads, and can transport goods heavier and larger (and cheaper) than an aeroplane (B747 can carry 110 tonne) and faster than a surface ship (days rather than weeks).

Conventional airships of the rigid and non-rigid forms have generally had payloads less than 50 tonnes. The Hindenberg, the largest airship built to date had a lifting gas capacity of 200 000 m^3 and was 245 m long. The largest non-rigid airships flown (*ZPG-3W*) had a 40 ton lifting capacity. The Sentinel 5000 extends this to about 50 tons. What is being envisaged now are large airships up to 400m in length with payloads of 50-500 tonne (Figure 15.38).

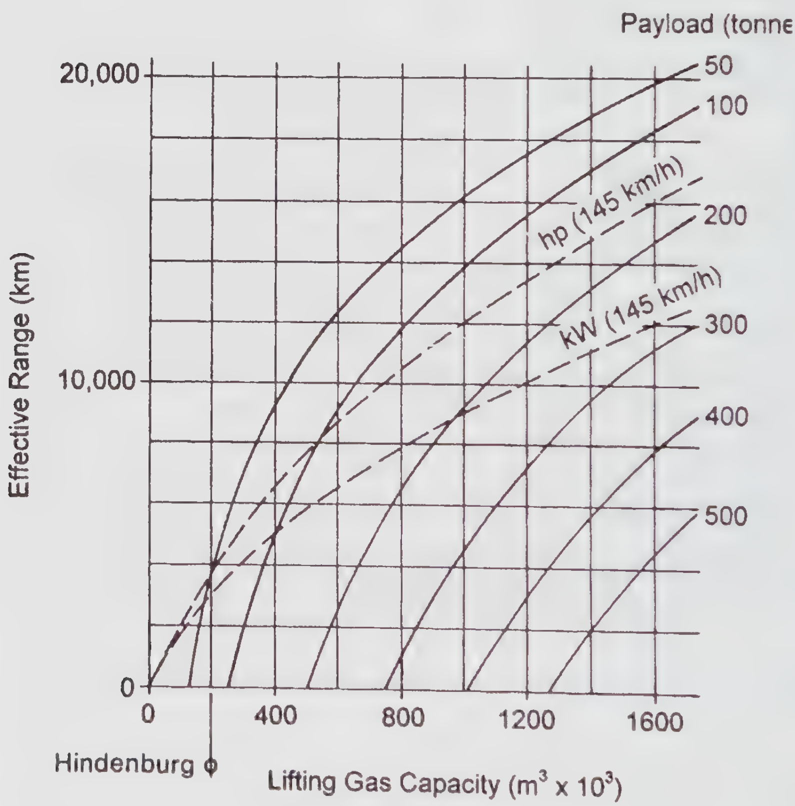


Figure 15.38. Generalised heavy lift airship performance (Mowforth, 1991).

Buoyancy is maintained by vectored thrust or associated techniques with a constant-weight combination of fuel, payload and ballast. 'Load exchange' is then carried out between one of the three components and another through appropriate ground handling. Airships are, therefore, divided into three categories according to the manner in which load exchange is carried out, namely: (a) Field loading with mobile handling facilities; (b) Base loading with a fixed terminal; and (c) air loading in hovering flight by means of an on-board hoist system or auxiliary aircraft. The method selected largely depends upon the airship size (Figure 15.39).

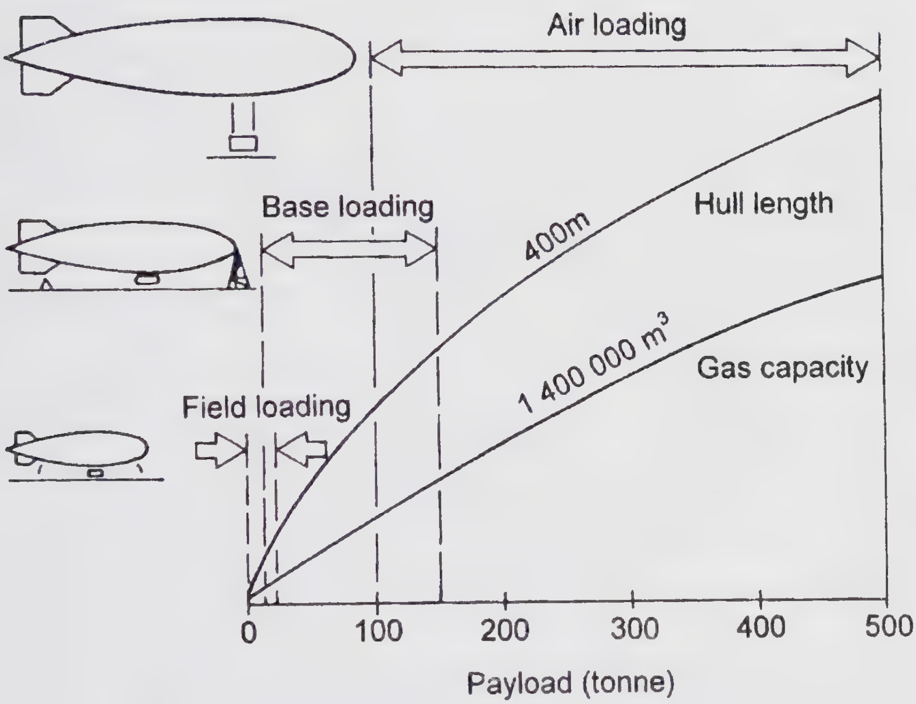


Figure 15.39. Airship loading categories (Mowforth, 1991).

A pioneer in the concept of Heavy Lift (HL) is Dr Edwin Mowforth who designed in the U.K. a series of *Airfloat HL* rigid airships from 1969 to 1975 (Figure 15.40). The airships were intended to carry large indivisible loads of almost any shape or size and weighing up to 500 tonne, over distances of 1000-2000km, loading and unloading in hovering flight (Mowforth, 1991).

In 1996, Mowforth acted as consultant to a German company CragoLifter AG whose president Dr. Carl von Gablenz has conceived the semi-rigid *CL160* transporter (gas volume 350 000 m^3, length 240 m, height 60 m) with a loading bay capable of carrying loads up to 50m x 8m x 8m in size and 160 tonne in weight. A market survey carried by the CargoLifter company amongst 10 German machine and plant manufacturers indicated that there were annually 300 Shipments with individual weights greater than 100 tonne, or with a length more than 25 metres, or with a diameter greater than 4 meters (von Gablenz, 1996).

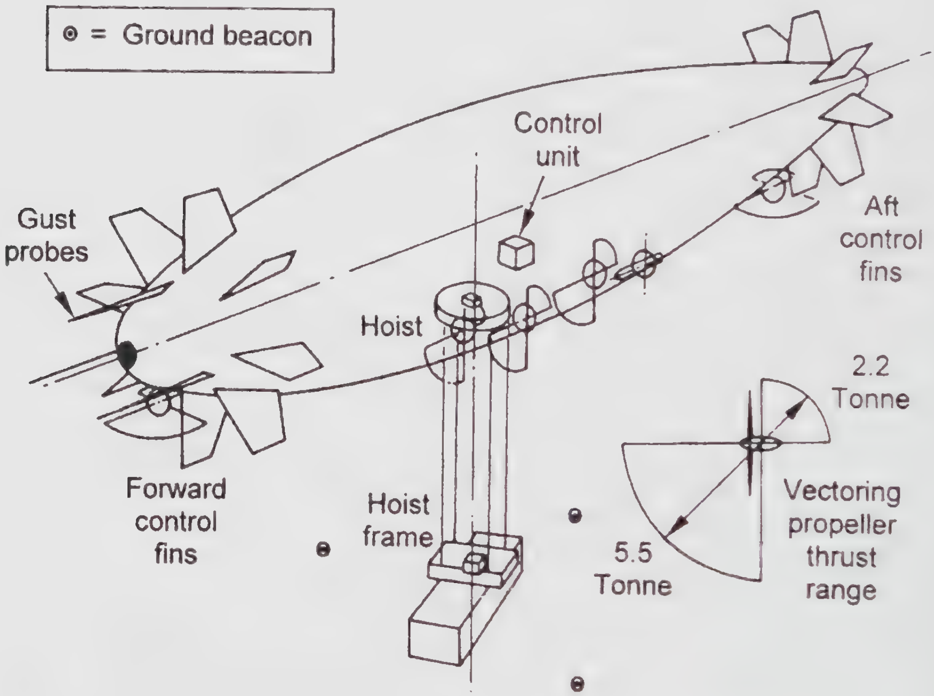


Figure 15.40. Airfloat HL hovering control system (Mowforth, 1991).

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16

Solar Power

G. Khoury

INTRODUCTION

Solar energy is attractive in an environmentally conscious age. Sunlight is a renewable, 'free', non-polluting and non-inflammable fuel. A solar-powered airship would not require re-fuelling when operating in remote sunny areas of the world or at high altitudes, thereby achieving long endurance. A solar-powered airship is also a constant weight vehicle, and trimming problems associated with weight loss on fuel consumption do not arise.

A solar-powered airship is defined as an airship that attains its power for propulsion primarily from solar energy, albeit in conjunction with on-board energy storage for operations at night and in windy conditions.

Solar energy is a spatially distributed, and not concentrated, source of energy. At peak conditions, about 1,000 kW/m^2 of solar energy is received at sea level. However, because of the airship's inherently large surface area, and its relatively low power requirement, significant speeds can be achieved from solar power alone in sunny climates.

Commercial feasibility requires relatively low capital and running costs. It also depends on the operational capabilities of the airship. Technical feasibility requires that:

- the amount of solar energy received is sufficient for propulsion and for replenishing the required on-board storage unit. This depends primarily on the climate and on the conversion efficiency of the solar cells;
- the weight of the solar/electrical system is acceptable. The weights of the solar cells and the on-board storage units are key factors in this respect.

This chapter provides details of theoretical/parametric calculations to show that, in principle, sufficient speeds could be achieved from solar power alone. The key elements of the hardware (e.g. solar cells, electric motors, collector grid network, and storage units) are also discussed. Last but not least, basic weight and cost considerations are discussed.

OUTLINE OF THE 'SUNSHIP'

The solar-powered airship '*Sunship*', proposed by the author (Khoury and Mowforth, 1978) (Khoury, 1986), comprises in its simplest form a conventionally shaped helium filled airship powered by electric motors driving propellers and supplied with electrical current mainly from an array of black flexible thin film solar cells covering an appropriate part of its skin area (Figure 16.1).

The solar cells generate electrical power which is collected and fed through a suitable grid and control system to electrical motors driving propellers (Figure 16.1). The control system comprises a computer controlled power conditioner capable of converting variable voltage direct current from the solar cells to controlled voltage direct current energy, with an efficiency exceeding 90%. A proportion of the energy produced by the solar cells is diverted to a suitable on-board storage installation possessing a high energy storage-to-weight ratio.

The energy required for flight-services such as lighting and instrumentation could be obtained directly from the grid system or from the storage units. Additional power, and operational flexibility in gusty weather or at the beginning and end of the day, is provided by the storage units.

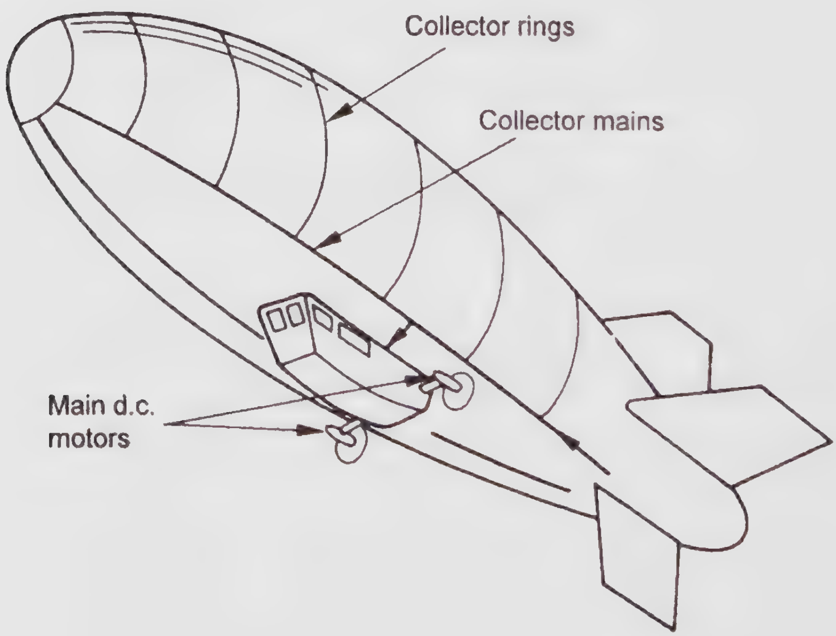


Figure 16.1. Direct current collector network (Khoury and Mowforth 1978 a & b).

The on-board computer controls the proportion of power fed into, or from, the storage units on the basis of the balance between the available supply from the solar cells and the demand from the pilot for power to the motors (Figure 16.2).

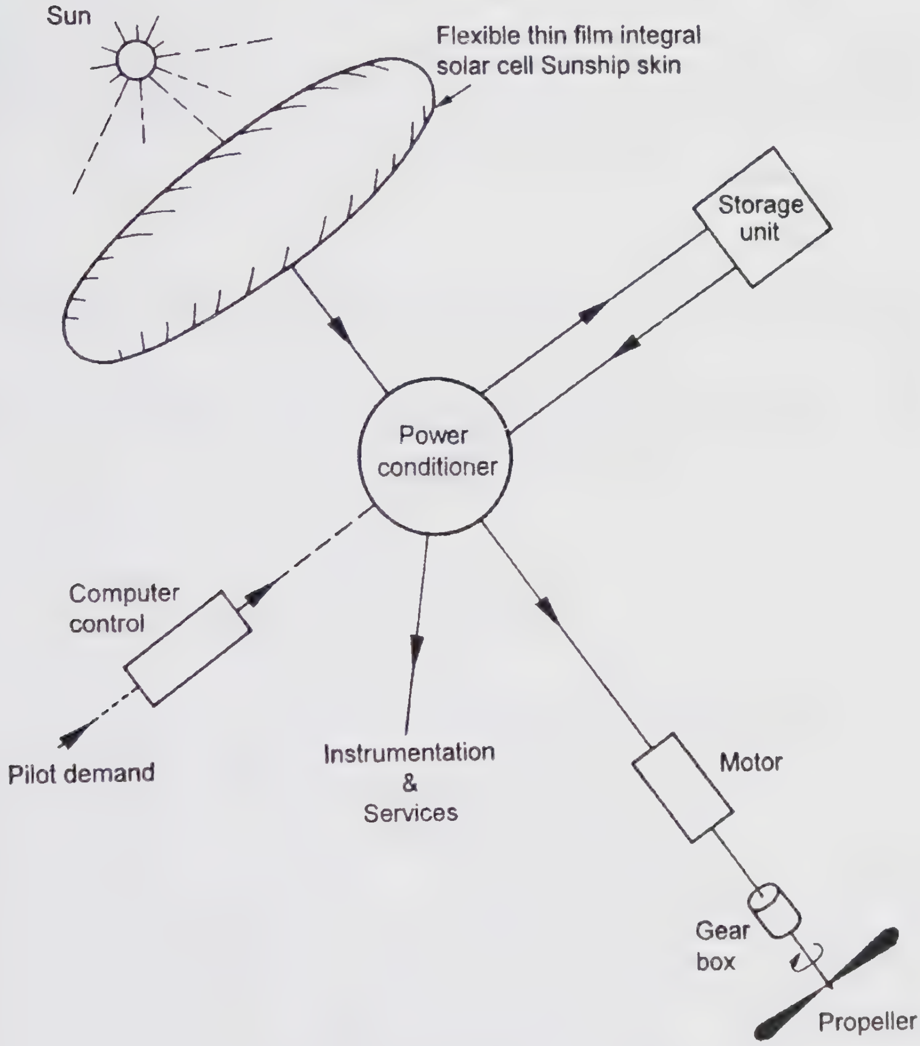


Figure 16.2. Outline of the solar power system (Khoury 1986).

SOLAR RADIATION

The solar energy reaching the upper limits of the Earth's atmosphere is about 1,353 W/m^2. As 'direct' solar radiation travels through the atmosphere it is selectively absorbed and scattered such that when it reaches sea level on a clear day it is attenuated by about 30% and its spectral distribution is significantly altered. The degree of attenuation of direct solar radiation depends on the 'air mass', defined as the path length of clear atmosphere through which solar radiation penetrates before reaching ground level. An air mass of unity (m = 1) is the amount of atmosphere encountered at sea level by the sun's rays in a direct radial path when the solar altitude 'A' is 90^o (Figure 16.3). The irradiation at m = 1 for a very clear atmosphere is about 956 W/m^2 at sea level. For solar altitudes greater than about 20^o, the air mass can be approximately represented by:

$$m = 1/\sin A \tag{16.1}$$

The solar altitudes at sea level for air masses of 1, 2 and 3 are 90^o, 30^o, and 20^o respectively.

The total solar radiation at ground level is the sum of the direct and 'diffused' (i.e. scattered) components. 'Reflected' solar radiation may also be received from surfaces such as mountains, snow clouds and desert sands.

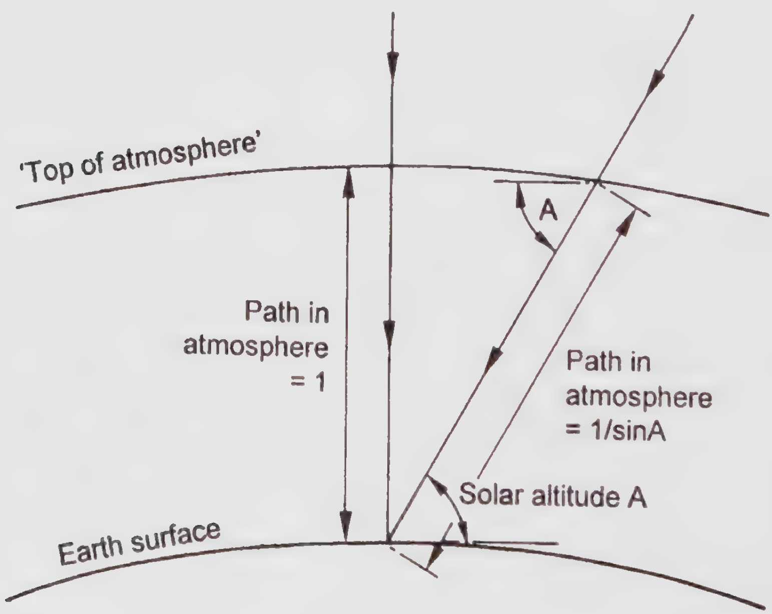


Figure 16.3. Length of ray path in the atmosphere (Brinkworth, 1972).

Direct Solar Radiation

Direct solar radiation is sensitive to the water content of the air and reduces with increase in atmospheric humidity. Atmospheric pollution causes a significant reduction in direct solar radiation and the effect is more pronounced at higher air masses. The 'peak' value of 956 W/m^2 is reduced by 16% to 800 W/m^2 or even less for a very polluted atmosphere although this is partially compensated by an increase in the diffuse component.

Direct solar flux normal to the Sun's rays 'D', at sea level and for clear sky conditions, is expressed as a function of solar altitude 'A' by the following equation (Meinel and Meinel, 1976):

$$D(A) = D_o e^{-c[\csc A]^s} \qquad (16.2)$$

where Do is the solar constant (1.353 kW/m^2) and the two empirical constants are c = 0.357 and s = 0.678, and where csc A = 1/sin A = sec λ (λ = zenith distance).

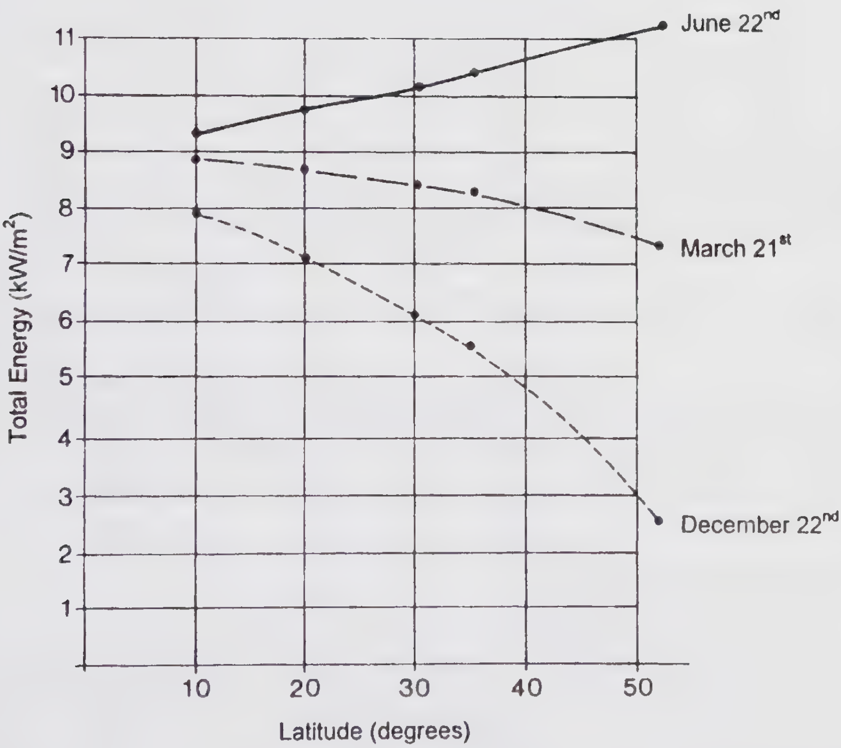


Figure 16.4. Effect of latitude and time of year on the normal direct solar energy received per day under cloudless conditions (Khoury, 1986).

Equation 16.2 shows that, for clear sky conditions, the normal direct solar flux is only a function of the solar altitude. The solar altitude can be determined by the following formula:

$$\sin A \;=\; \cos N \cos H \cos L \;+\; \sin N \sin L \tag{16.3}$$

where 'L' is the latitude on Earth in degrees (0^{o} for the Equator) and 'H' is the hour angle at time 't' after solar noon i.e.:

$$H \;=\; (t/24) \times 260^{o} \;=\; 15t \text{ degrees} \tag{16.4}$$

and 'N' is the declination which represents the seasonal variation in the Sun's apparent position. N varies between $+23.5^{o}$ at the Summer solstice and -23.5^{o} at the Winter solstice. If we measure the time of year in days from the Spring Equinox (March 21st) the declination is given approximately by:

$$N \;=\; 23.5 \sin(2\pi d/365) \text{ degrees} \tag{16.5}$$

Equation 16.3 shows that direct solar flux is significantly influenced by the latitude on Earth (Figure 16.4). For latitudes less than 35^{o}, the clear sky radiation exceeds 500 W/m^2 for at least 7 hours a day throughout the year. In contrast, the December 22 figure for latitude 52^{o} (London) is less than 1 hour.

Direct solar flux also increases with altitude above sea level as the air mass diminishes (Figure 16.5). It reaches the solar constant outside the atmosphere, nominally taken as 30 km above sea level. Equation 16.2 is modified, using data by Laue (1970), to take into account the altitude above sea level 'h':

$$D(A,h) \;=\; D_o(\,1-a\,h)\, e^{-c[\csc A]^s} + a\;\, h\;\, D_o \tag{16.6}$$

where a = 0.14 per km of altitude. This formula is, however, applicable for only the first few kilometres altitude. The maximum direct solar flux increases by about 6% at latitude of 1 km and by about 17% at 3 kms. The proportional increase is larger for smaller solar altitudes.

Diffuse Solar Radiation

The diffuse (i.e. scattered) sky radiation comes from the entire sky, scattered by particles or molecules in the air, and can be collected but not optically focused. It should not be confused with atmospheric thermal radiation which has much longer wavelengths. The spectrum of diffuse sky radiation is shifted slightly towards the shorter wavelength compared with that of direct radiation.

The diffuse irradiation is influenced by the air mass. For a very clear atmosphere, it can vary from about 90-110 W/m^2 for m = 1 to about 40-70 W/m^2 for m = 3. It is also significantly affected by atmospheric turbidity; in an urban location it can be more than double the value for a desert location.

Cloud cover has a significant influence on the diffuse radiation. On an overcast day, the diffuse component can be 100% of the relatively small total. In the summer months, with high Sun and broken cloud, the diffuse irradiance can be as high as 400 W/ m^2 and commonly exceeds 200 W/ m^2. Some 60% of the annual radiation in the UK is received as diffuse radiation.

A horizontal surface receives the full complement of diffuse radiation. For an inclined surface, the amount is reduced by a factor which can be assumed to decrease linearly with slope from 1.0 for horizontal surfaces to 0.5 for vertical surfaces. For the purpose of calculating the diffuse sky radiation incident on the Sunship in flight, however, it is assumed that the diffused component has a 2π distribution and falls evenly on the top half of the hull's surface.

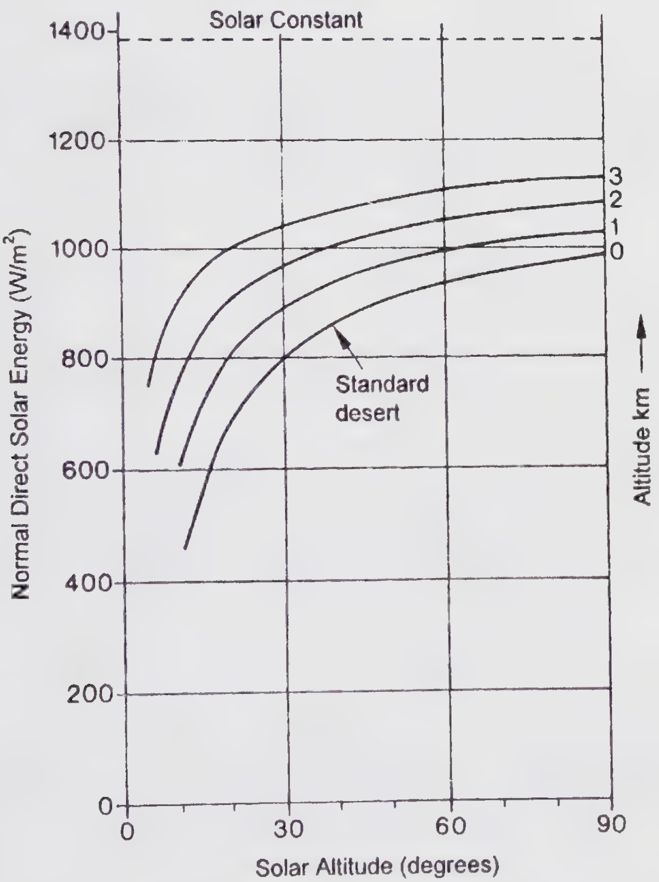


Figure 16.5. Effect of altitude above sea level on the direct normal solar flux as a function of solar altitude (Meinel and Meinel, 1976).

Reflected Solar Radiation

Clouds and ground surfaces reflect sunlight, which adds to the total scattered flux but is not strictly diffuse in nature.

The reflection of surfaces is expressed in terms of the 'albedo' or surface reflectance. Desert sand can have an albedo of 0.4 while the albedo of clouds, which do not absorb much energy, can be as high as 0.9. The high reflectance of snow at the poles causes a significant loss of solar radiation back into the sky.

A tilted collector would receive reflected radiation from the ground and diffuse radiation from the sky. In calculating the amount of reflected radiation incident on the Sunship from the ground, it is assumed that the component has a 2π distribution and falls evenly on the bottom half of the hull's surface.

SOLAR-POWERED FLIGHT SPEED

Solar Radiation Conditions

The solar-powered flight speed of the Sunship is calculated in this section using the solar irradiation figures given in the previous section for cloudless conditions and for an atmosphere of low water content and low turbidity.

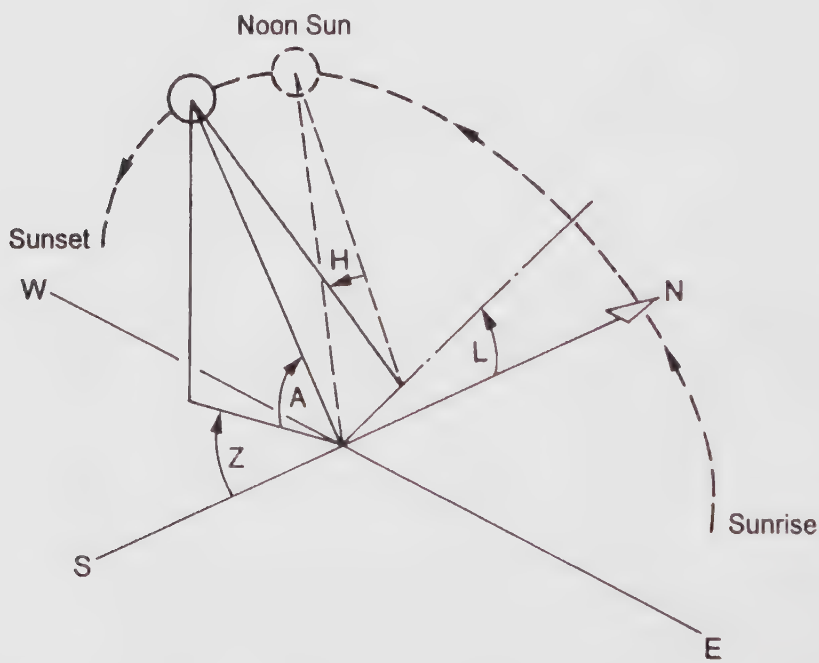


Figure 16.6. Apparent motion of the Sun at latitude 'L' in the northern hemisphere (Brinkworth, 1972).

Angle of Solar Incidence

The angle of solar incidence 'B' between the Sun's rays and the Sunship's major axis (direction of flight) is required for calculating the area projected by the Sun's 'parallel' rays. Angle 'B' can be determined by vector analysis using the same rectangular co-ordinate system as defined in Figure 16.6 for calculating the Sun's position in the sky in terms of the solar altitude 'A' and the solar azimuth 'Z'.

The solar azimuth 'Z' is the angular distance of the Sun from true north (Geographic not magnetic) measured clockwise around the horizon and can be calculated as follows:

$$Z = \sin^{-1}(\cos N \sin H / \cos A) \quad (16.7)$$

A unit vector **S** along the Sun's rays can be expressed in terms of the angles of solar altitude and azimuth as shown in Figure 16.7.

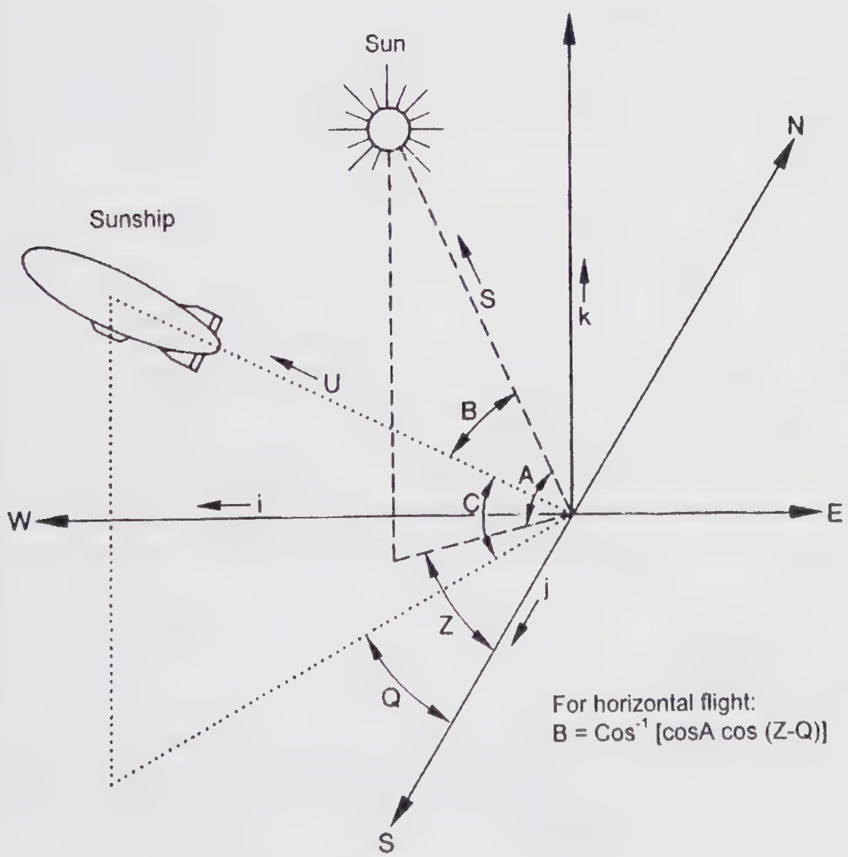


Figure 16.7. Angle of solar incidence 'B' between the Sun's rays and the Sunship's major axis (Khoury, 1986).

Its component vectors in the **i** (E-W), **j** (N-S), and **k** (global radial) directions are:

$$\mathbf{S} = \cos A \sin Z\,\mathbf{i} + \cos A \cos Z\,\mathbf{j} + \sin A\,\mathbf{k} \tag{16.8}$$

A unit vector **U** along the Sunship's major axis is also expressed in terms of an angle 'C' measured vertically from the horizon and an angular distance 'Q' measured clockwise from true geographic north (Figure 16.7). Its component vectors become:

$$\mathbf{U} = \cos C \sin Q\,\mathbf{i} + \cos C \cos Q\,\mathbf{j} + \sin C\,\mathbf{k} \tag{16.9}$$

The incident angle B is the angle between the two vectors which is determined by a dot product (Khoury, 1986):

$$B = \cos^{-1}(\cos A \sin Z \cos C \sin Q + \cos A \cos Z \cos Q + \sin A \sin C) \tag{16.10}$$

The angle of solar incidence B can, therefore, be calculated using Equation 16.10 for any time of day, latitude on the Earth's surface, season, and orientation of the Sunship. It also gives the angle of incidence even when the Sunship is climbing or descending. For horizontal flight, angle C would be zero and Equation 16.10 simplifies to:

$$B = \cos^{-1}(\cos A(\sin Z \sin Q + \cos Z \cos Q))$$

$$= \cos^{-1}(\cos A \cos(Z-Q)) \tag{16.11}$$

This simple equation confirms the common-sense view that, when the solar altitude 'A' is 90^o, the incident angle 'B' is also 90^o and independent of the orientation of the Sunship in the horizontal plane. When the solar altitude is 0^o, the incident angle can vary from 0^o to 90^o depending on the Sunship's orientation. The general rule is that, for horizontal flight, 'B' cannot be less than 'A' and is greater than 'A' for all orientations except when Q = Z. Also, for any solar altitude, there are two orientations of the Sunship which provide an angle of incidence of 90^o and hence a maximum projected area.

Projected Area

For ease of initial analysis, the Sunship's hull is idealised to a symmetrical ellipsoid entirely covered by a solar-sensitive skin and uninterrupted by gondola or empennage (Figure 16.8). The wetted surface area 'A_w' is expressed by:

$$A_w = 2\pi b\left[b + \frac{a^2}{\sqrt{a^2-b^2}}\sin^{-1}\left(\frac{\sqrt{a^2-b^2}}{a}\right)\right] \tag{16.12}$$

where 'a' is half the length of the major axis (L/2) and 'b' is the radius (= d/2).

The direct rays of the Sun would only fall on a proportion of the total wetted area at any one time. The effective receptive area is the 'projected' area 'A_p' (Figure 16.8) calculated as a function of the angle of solar incidence 'B' and the Sunship's axial length 'L' and diameter 'd':

$$A_p = \frac{\pi d^2}{4}\left(\sqrt{\cos^2 B + n^2 \sin^2 B}\right) \qquad (16.13)$$

where n = L/d

The maximum projected area 'A_{pmax}' for an angle of incidence of 90° becomes

$$A_{pmax} = \pi L d / 4 \qquad (16.14)$$

The minimum projected area A_{pmin} for an angle of incidence of 0° becomes:

$$A_{pmin} = \pi d^2 / 4 \qquad (16.15)$$

The ratio 'f' of the projected area for any incident angle 'B' to the maximum projected area becomes (Khoury 1986):

$$f = \frac{A_p(B)}{A_{pmax}} = \sqrt{\frac{\cos^2 B}{n^2} + \sin^2 B} \qquad (16.16)$$

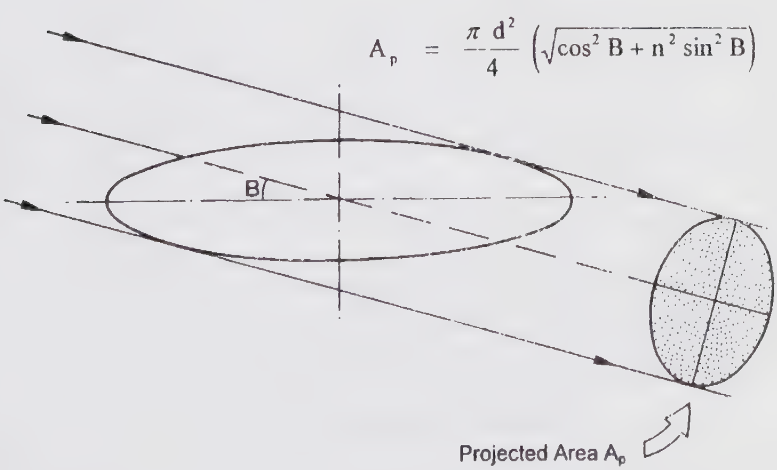


Figure 16.8. Area projected by the Sun's 'parallel' rays (Khoury, 1986).

This relation indicates that 'f' reduces with increase in 'n' for low angles of incidence (Figure 16.9) thus tending to favour a low value of 'n'. For example, the minimum value of 'f' at B = 0 is 0.5 and 0.2 for n of 2 and 5 respectively. In latitudes up to 30^o, however, the solar altitude exceeds 20^o for at least six hours a day throughout the year. If we consider angles of incidence above about 20^o, there is only a 7% difference in 'f' between 'n' values of 3 and 5.

The lowest value of 'f' (i.e. ratio of minimum to maximum projected areas) is, therefore:

$$f_{min} = A_{pmin} / A_{pmax} = 1/n = d/L \tag{16.17}$$

The minimum projected area is only 28.75% of the maximum value (d/L = 0.2875) but this occurs only early in the morning or late in the evening for one orientation of the Sunship. Regardless of the solar altitude, however, there are two orientations of the Sunship which provide the maximum projected area.

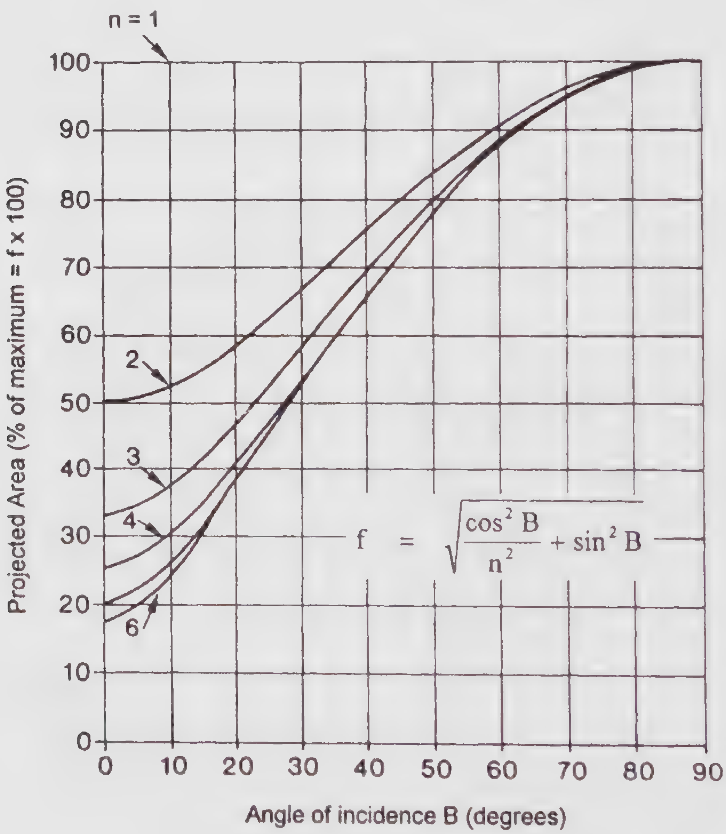


Figure 16.9. Projected area as a function of angle of solar incidence 'B' and the Sunship's length/diameter ratio 'n' (Khoury, 1986).

The ratio 'g' of the projected area to the total wetted surface area is, therefore:

$$g = A_p / A_w \tag{16.18}$$

For a Sunship with n = 3.48, the minimum and maximum values of 'g' would be 8.8% and 30.8% respectively (Figure 16.10)

Available Solar Energy

The direct solar energy 'E_D' falling on the Sunship can be estimated by multiplying the incident direct normal solar flux 'D' by the projected area 'A_p':

$$E_D = D \times A_p \tag{16.19}$$

The scattered sunlight contribution is estimated separately for the diffuse (sky) radiation 'S_d' and the reflected (ground) radiation S_r.

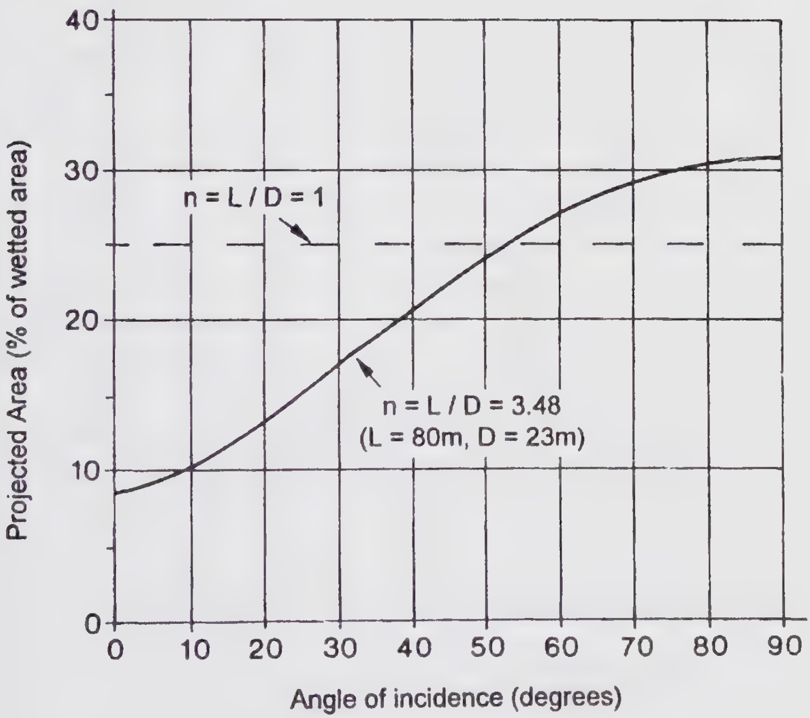


Figure 16.10. Projected area of the Sunship (as percent of the wetted surface area) against the angle of solar incidence (Khoury, 1986).

It is assumed, as a first approximation, that both 'S_d' and 'S_r' have a 2π distribution. The diffuse sky irradiation is, therefore, assumed to fall evenly on the top half of the Sunship's surface and the reflected component to fall evenly on the lower half. The total contribution from scattered radiation 'E_s' would be:

$$E_s = S_d A_w / 2 + S_r A_w /2 = A_w (S_d + Sr) / 2 \tag{16.20}$$

The <u>total</u> energy 'E_t' falling on the Sunship becomes:

$$E_t = E_D + E_s = A_p D + A_w (S_d + S_r) / 2 \tag{16.21}$$

In conventional airship design this energy is reflected away by the use of a white or silver coating to avoid superheating.

Efficiency of the Solar power System

The available solar energy suffers a series of reductions as it is converted into propulsive power. The total efficiency of the solar power system 'γ_t' is:

$$\gamma_t = \gamma_a \times \gamma_c \times \gamma_e \times \gamma_g \times \gamma_p \tag{16.22}$$

where:

γ_a = Solar cell packing area efficiency

γ_c = Solar cell conversion efficiency

γ_e = Electrical components efficiency

γ_p = Propulsive efficiency

Available Propulsive Power

The power available for propulsion 'P' is

$$P = E_t \times \gamma_t \tag{16.23}$$

Solar-Powered Flight Speed

A typical cubic power-speed relation for an airship is:

$$P = C_D \rho A_w V^3 / 2 \tag{16.24}$$

where:

C_D = Drag coefficient

ρ = Air mass density

A_w = Wetted surface area of the hull
V = Speed of the airship

The speed, therefore, becomes:

$$V = (2P/C_D A_w)^{1/3} \tag{16.25}$$

Example Calculations

Considering, as an example, an airship 80m long and 23m in diameter, the total hull volume would be about 22,000 m^2. The corresponding wetted surface area would be 4,677 m^2.

The maximum direct solar flux D_{max} expected to fall on the Sunship at an altitude of 1,000m at solar noon is about 1,000 W/ m^2. Assuming the incident angle to be 90°, the maximum direct solar energy E_{Dmax} available for conversion to electrical energy and eventually to propulsive power is A_{pmax} x D_{max} = 1,445 kW.

The maximum expected scattered component E_{Smax} is calculated to be 1,169 kW assuming a reflected desert sand component of 400 W/m^2 and a diffuse sky component of 100W/m^2. S_{max} is, therefore, estimated to be about 81% of the maximum contribution from direct radiation. This represents a 'maximum scenario' in terms of incident solar energy. Depending upon weight and cost considerations etc., it may be that in practice only parts of the top half of the airship would be covered with solar cells .

The total available energy 'E_t' becomes 2,614 kW for the maximum scenario. In conventional airship design this considerable amount of energy is reflected away by the use of a white or silver coating to avoid superheating.

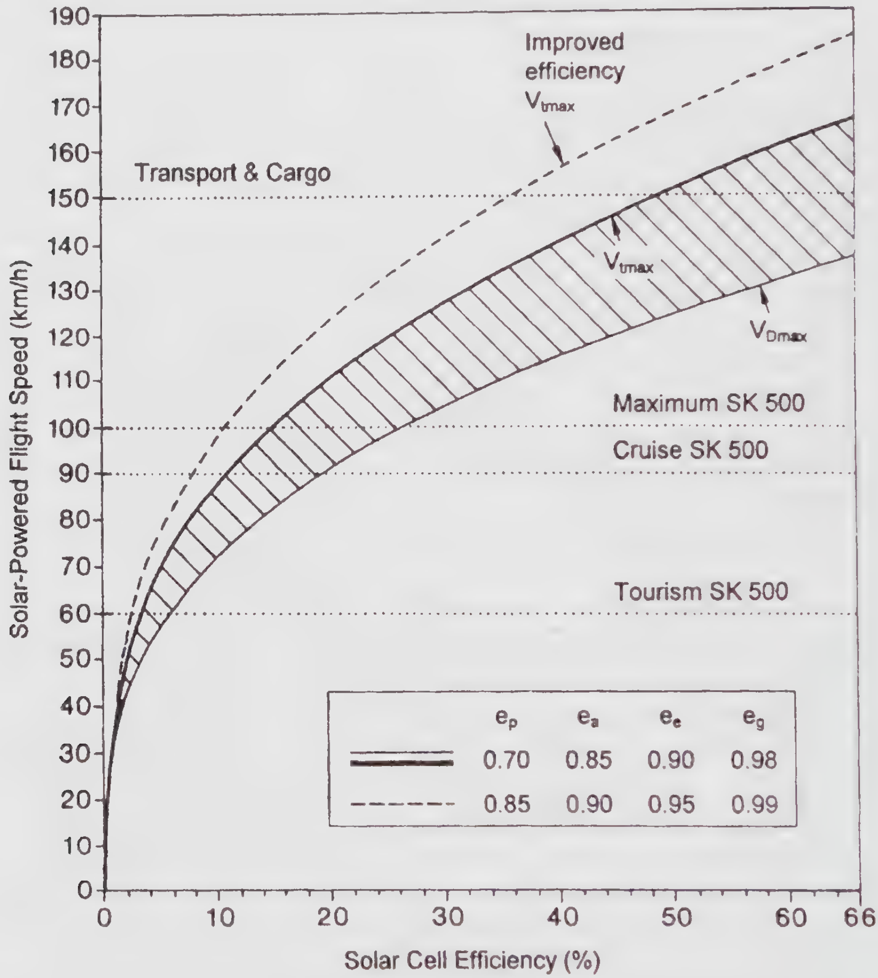
Considering a solar cell conversion efficiency 'γ_c' of 15% and a corresponding total efficiency 'γ_t' of 7.9% (γ_a = 85%, γ_e = 90%, γ_g = 98%, γ_p = 70%) the total maximum available propulsive power 'P_{tmax}' becomes 205 kW. For improved solar cell conversion efficiency of 66% (theoretical maximum) and an improved total efficiency 'γ_t' of 47.5% (γ_a = 90%, γ_e = 95%, γ_g = 99%, γ_p = 85%), P_{tmax} becomes 1,241 kW.

Considering a power-speed relation of $V = 17.1\ P^{1/3}$ (P in kW, V in km/h) the maximum speed V_{tmax} becomes 101 km/h and 184 km/h for 'γ_t' values of 7.9% and 47.5% respectively. These speeds are acceptable for tourist and cruise applications. The corresponding speeds obtained from direct solar energy E_D alone are 83 km/h and 151 km/h respectively.

The solar power speed is given in Figure 16.11 as a function of solar cell efficiency for the two sets of values of electrical conversion efficiency. The contributions of the direct and scattered solar radiation are also shown (Khoury 1986).

The foregoing calculations are based on the assumption that the energy received from solar irradiation is channelled entirely to propulsive power. In practice, any surplus to requirements energy will be channelled to the on-board storage unit and to instrumentation etc. Conversely, on-board storage energy will be available to provide additional propulsive power when required.

The power-speed relation given in Figure 16.12 for $V = 17.1\ P^{1/3}$ shows that a doubling of the propulsive power results in only a 27% increase in speed whereas halving of the power will result in only a 20% reduction in speed. The speed is, therefore, a damped response to variations in power input. This phenomenon becomes beneficial when the power input reduces due to changes in the orientation of the Sunship or due to a decrease in solar altitude with time of day or season.



V_{Dmax} & V_{tmax} are the speeds obtained from direct and total irradiation respectively. e_p, e_a, e_e, e_g are the propulsion, cell area, electrical and gear efficiencies respectively.

Figure 16.11. Solar powered flight speed versus cell efficiency under peak solar conditions (100 W/m^2 direct, 100 W/m^2 sky diffused, 400 W/m^2 ground reflected radiation) for an airship totally covered with solar cells (Khoury, 1986).

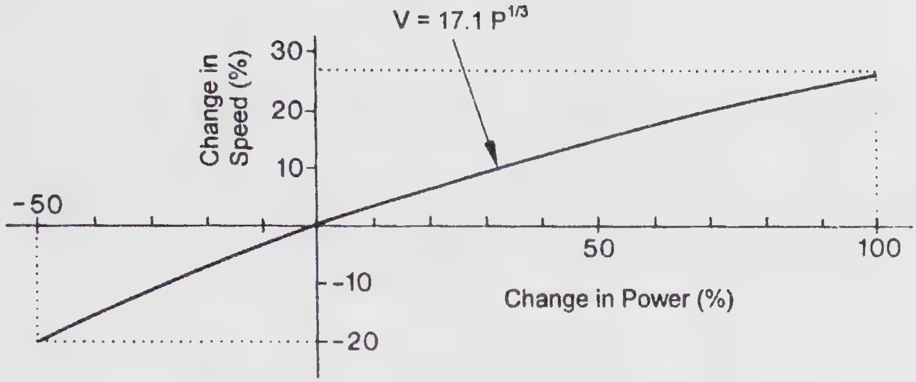


Figure 16.12. Power-speed relation of the Sunship (Khoury, 1986).

Figure 16.13 illustrates this point for hourly variations in solar-powered flight speed (for latitude 20^{o} and for solar cell conversion efficiency of 20%) calculated for direct radiation only. The influences of orientation, season, and time of day are shown not to be too marked between the hours 8 am and 4 pm (Khoury and Mowforth 1978).

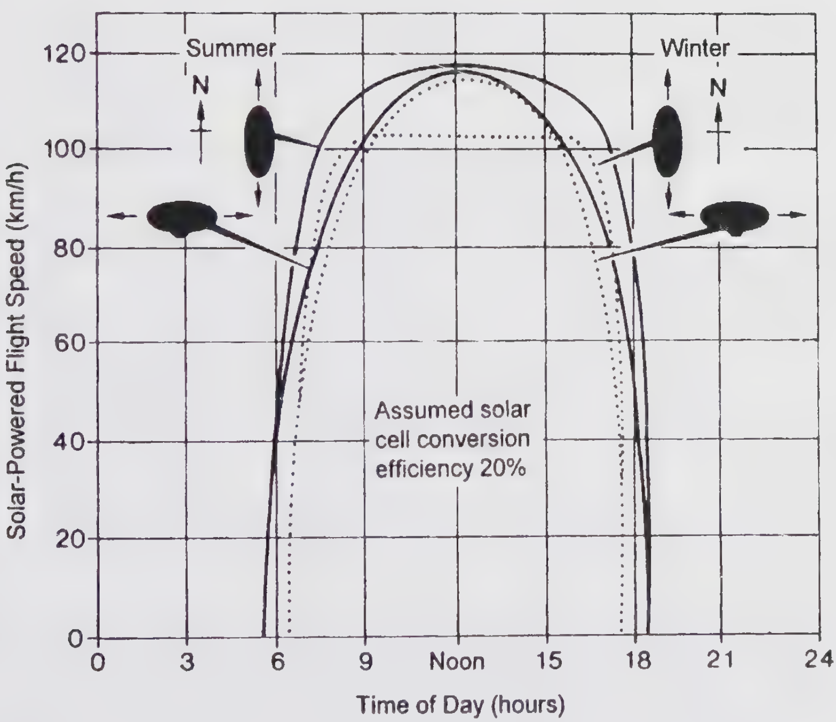


Figure 16.13. Effect of time of day, season and orientation of the Sunship on its solar powered flight speed at latitude 20° without power contribution from the storage units (Khoury and Mowforth, 1978).

COMPONENTS OF THE SOLAR POWER SYSTEM

Solar Cells

The type of solar cell suitable for airship applications will be a stable, low cost, flexible, lightweight, and high efficiency thin film (<20 microns and can be 1-2 microns thick) cell, ideally deposited on the airships' envelope material of equal durability and with which it is mechanically and thermally compatible within the working range of conditions. This configuration produces an integral solar-cell envelope skin of minimum weight and maximum mechanical flexibility.

Characteristics

Solar cells are photovoltaic devices which convert a proportion of the frequency of sunlight into usable direct current (dc) electricity. A solar cell consists of a thin slice of semiconductor material comprising a junction sandwiched between n- and p-type sections with electrical contacts on both faces as shown in Figure 16.14.

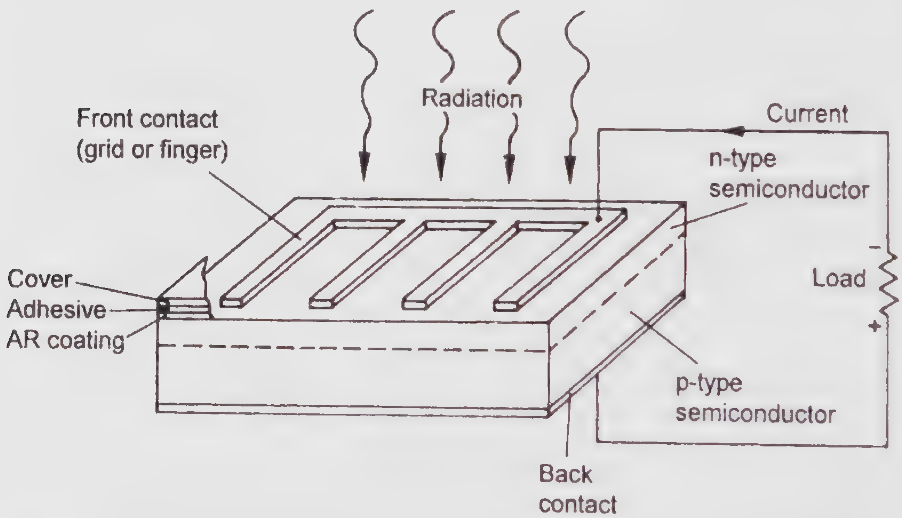


Figure 16.14. Schematic diagram (not to scale) of a solar cell (Burke, 1981).

The cell is covered by a selective protective coating which reduces the reflection of the incident light. Inevitably some conversion into heat takes place (Figure 16.15) which should be conducted and radiated away as effectively as possible, since an increase in temperature causes a reduction in conversion efficiency. In a typical case, an increase in operating temperature from 20°C to 100°C reduces output by more than a third (Brinkworth, 1972). Movement of the airship would assist in air-cooling of the cells and results in a higher efficiency relative to a stationary cell. The relation between the current density 'i' and the output voltage 'v' of a cell is shown in Figure 16.16.

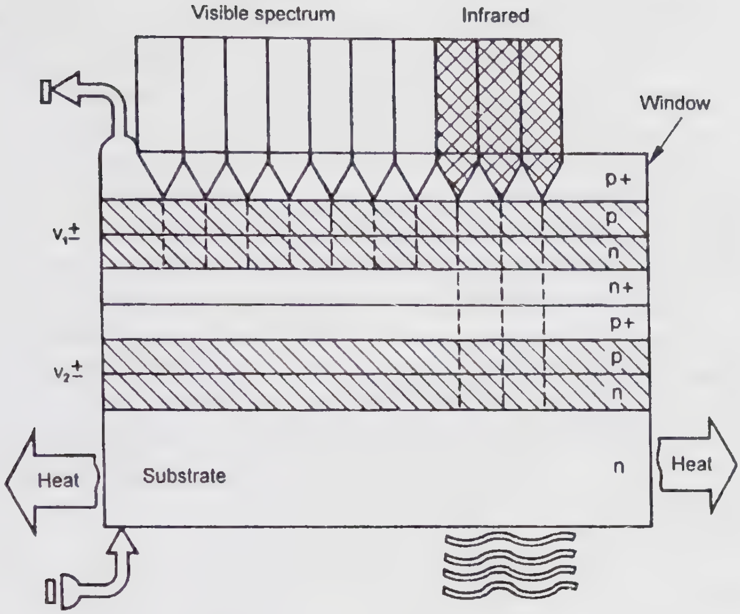


Figure 16.15. Schematic diagram (not to scale) of a multi-junction solar cell (Burke, 1981).

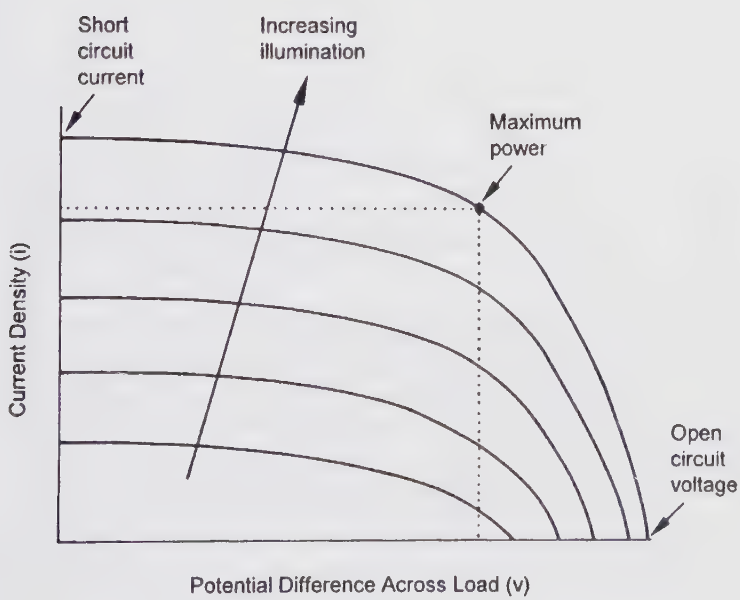


Figure 16.16. Typical solar cell power output characteristics.

The total current generated is directly proportional to the cell area 'a' and intensity of falling sunlight, while the voltage changes more slowly with light intensity, and is proportional to the logarithm of intensity. When exposed to sunlight, the total power produced by the cell in a load is equal to 'i x v x a'. The operating condition for which this product is greatest is when the rectangle inscribed within the characteristic curve has the largest area which occurs at the 'knee' of the curve (Figure 16.16). At this point, the output current is less than the 'short-circuit current' and the output voltage is less than the 'open-circuit voltage'.

A typical solar cell produces about 0.6 volts. Cell sizes and shapes vary but a typical area of about 10 cm x 10 cm also produces a current of about 3 amps under full direct sunlight. The output voltage can be increased by connecting cells in series and the total voltage becomes the sum of the voltages from each cell. By connecting the cells in parallel, the output becomes the sum of all the currents at the voltage of an individual cell. Typically, the cells are connected in both series and parallel into sub-arrays which are in turn electrically inter-connected to obtain the desired system voltage and current.

Efficiency

The efficiency of the solar cells is a key parameter because it determines directly the power produced per unit area. Generally, efficiency influences both cost and weight, since a higher efficiency means that, for the same power output, a smaller array area and less installed space are required.

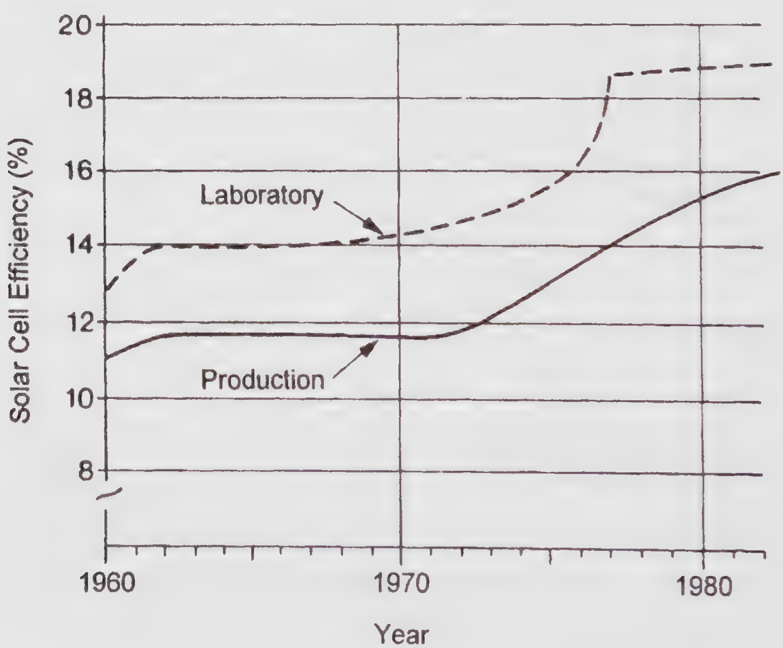


Figure 16.17. Historical evolution of solar cell efficiency (Graves, 1982).

Efficiencies of solar cells available on the market have increased significantly since about 1970 but as expected they lagged behind the efficiencies produced in laboratories by a few years (Figure 16.17).

Efficiencies of laboratory produced solar cells are approaching the theoretical efficiency of individual types of cells (Figure 16.18).

Solar cell efficiencies could be increased above the theoretical maximum for any given type by stacking thin film cells to form a multi-layer, multi-junction cell capable of utilising a wider wavelength range of the solar spectrum (Hamakawa, 1985). Each layer would absorb a different part of the spectrum (Figure 16.17) the voltage generated by each cell can then be added together and the device efficiency will approximately be the sum of the efficiencies of each cell. Stacked cells may have up to 11 layers (New Scientist, 1985). By appropriate choice of materials, a maximum theoretical efficiency of 66% can be expected from a multi-layered solar cell (Hill, 1986).

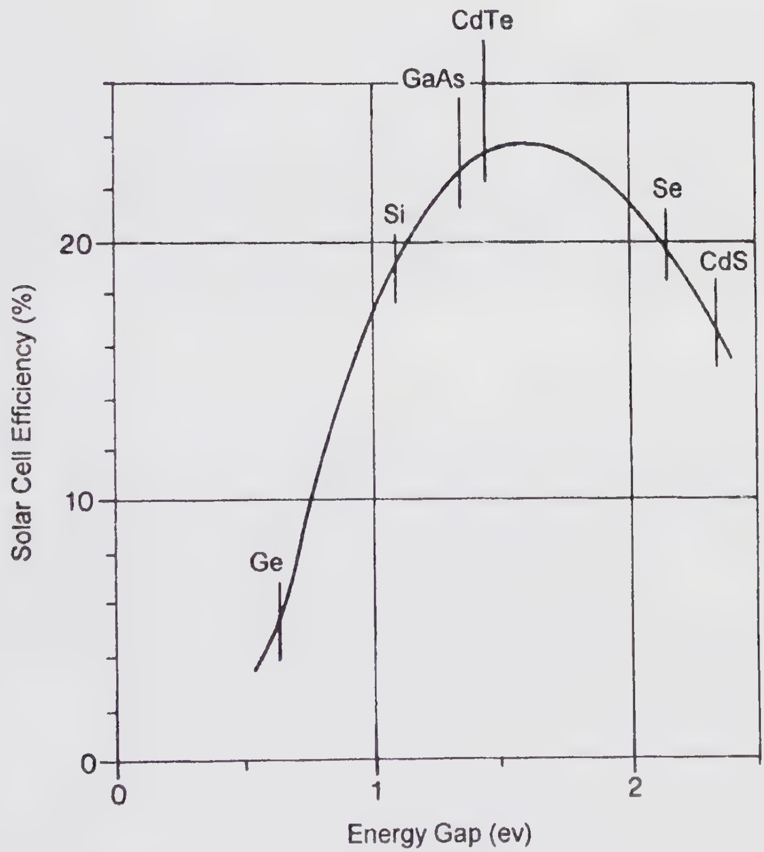


Figure 16.18. Relative efficiency of solar cells (Ravich, 1964).

In amorphous silicon solar cells, the layers nearest to the light source will be sensitive to the shorter wavelengths with an efficiency of about 7%; the centre layers would be sensitive to wavelengths around 0.6 microns with an efficiency of at least 11% and the final layers are expected to convert the longer wavelengths with an efficiency of about 3%.

Another technique for improving efficiency is to deposit the cells on roughened substrates which produces higher efficiencies in the 0.6-0.7 micron region by extending the path of the light at the back surface of the solar cell (Grabe *et. al.*, 1985).

The efficiency of a module is always less than that of the individual cells because of mismatching of the output characteristics and because the area of the module is always greater than the sum of the areas of the cells. For a closely packed lattice of rectangular thin film cells, the total cell area may be about 85-90% of the module area (Hill, 1982).

Types of Cell

Crystalline Silicon Cells

Crystalline silicon (Si) cells are used in non-airship applications because of the abundance of silicon material. The cells are sliced from silicon crystals in an expensive and wasteful process. Efficiencies of 10-16% have been produced, while the theoretical maximum efficiency is about 25%. Their inflexibility and cost make them unlikely candidates for use on the flexible hull of an airship.

Amorphous Silicon Cells

Amorphous silicon (a-si) cells can be deposited in thin films 1-2 microns thick on inexpensive substrates, which need preheating to a relatively low temperature. Flexible substrates such as plastics could be used. The mechanical flexibility and low cost of the a-Si cell makes it potentially a suitable candidate for use on airships. The drawbacks to date have been, however, the relatively low efficiency of the cells (below 10%) and the decrease in efficiency under prolonged sunlight irradiation (Hill, 1986) (Solomon, 1985), although higher efficiencies have been obtained with stacked a-Si cells (Hamakawa, 1985) (New Scientist, 1985).

Gallium Arsenide Cells

Gallium Arsenide (GaAs) solar cells are much more expensive than Si cells and use relatively rare materials but they have higher efficiencies and tolerate higher temperatures than silicon cells. Efficiencies greater than 23% have been demonstrated and they also may be relatively easily produced in thin films. For viable airship applications, the price needs to be reduced and the cells deposited on suitable flexible substrates.

Polycrystalline Cells

Polycrystalline solar cells such as Cadmium Sulphide (CdS), Copper Indium Selenide, can be deposited in thin films less than 20 microns thick on flexible substrates at low temperatures (Burke, 1981) . CdS based cells have been deposited on Kevlar and on Kapton (Hill, 1986). The process can also be faster, simpler and cheaper than that of a-Si cells and uses less energy (Hill, 1982). Efficiencies greater than 11% have been achieved. Furthermore, CdS based cells do not suffer the deterioration experienced by a-Si cells and can be stable over a period of ten years and possibly more (Hill, 1979).

Collector Grid Network

The solar cell sub-arrays will have their own built-in connections. The main cables which feed the current produced by the sub-arrays to the power conditioner could be made of thin wide strips of metal to avoid concentrations of load on the envelope. The strips, insulated with PTFE, could be bonded to the internal surface of the envelope to avoid occupying external surface space (Khoury, 1986). They would also help reduce permeability of helium in those areas to which they are bonded. The collector grid network may add as much as 30% to the total weight of the solar cell skin (Hill, 1986). The circuitry could be designed such that a fault occurring in a sub-array would only affect the power supply from the sub-array. A design for a relatively high voltage would also reduce the current in the main feed cables and hence their size and weight.

Electric Motors

An electric motor suitable for airship applications should require minimum maintenance and be of low weight, low cost and high efficiency. The usually high weight of conventional dc motors has recently been reducing as aluminium replaces steel in the frames. The weight can be reduced significantly by the use of brushless dc motors (Bolton, 1986) (Davis, 1982) which possess efficiencies in excess of 90%. Brushless dc motors are synchronous ac motors with an inverter in which the magnetic field source is located on the rotor and takes the form of a permanent magnet and steel assembly. For high performance, rare earth magnets are invariably used. The ac windings, located on the stator, are switched electronically. The electronic circuitry thus replaces the conventional commutator. Being brushless, the motors are virtually maintenance free. They can also be more efficient, more reliable and have a better response time than conventional motors (Klass, 1977). Induction and particularly reluctance motors with inverters are cheaper, but are generally less efficient and their weight - including inverter - will be more than those of synchronous motors. They would therefore be less attractive for use in an airship.

Storage Units

Four options of power storage are briefly considered in this section: Secondary batteries, flow batteries, fuel cells and flywheels.

Secondary Batteries

A conventional battery contains its chemical reactants and its energy in an electrolytic cell. It can be non-rechargeable (primary) or chargeable (secondary). In batteries, the scaling of factors such as stored energy, weight and cost is linear on account of the multi-modular construction of the system. Potential values of 'specific energy' in Wh/kg range from 40 for the lead acid (Pb-acid) battery to 500 for the aluminium-air (Al-air) battery (Table 16.1). The overall battery efficiency is the ratio of the delivered to received energy, and ranges up to 80% (Graves, 1982). The amount of stored energy that can be withdrawn from the secondary battery without decreasing the overall efficiency is called the 'depth-of-discharge' . Values range up to 0.8 (Graves, 1982). For a specific battery, the number of charge-discharge cycles tends to be inversely proportional to the depth-of-discharge. The Al-air batteries recharged mechanically by replacing the aluminium electrode, and therefore would not make use of the surplus power produced by the solar cells. The Na-S battery operates at temperatures above 270°C which could be dangerous, but it has the advantage of a relatively high density and its voltage remains constant until 70% of the energy has been discharged (Hamer, 1986). The operating temperature can be achieved by discharging and charging the battery or by direct heating from the power drawn from the battery, both of which reduce its efficiency from the maximum of 85-90% to about 75%. Alternatively the cell may be heated from an external source (Scamans, 1986). Its depth-of-discharge is 0.8. Pocket type Nickel-Cadmium (Ni-Cd) and Nickel-Hydrogen (Ni-H_2) batteries with lifetimes up to 20 years, and recharged from solar cells, have been used in space applications where photovoltaic systems must operate in a maintenance free environment (Kordesch *et. al.*, 1985). Their specific energy is in the region of 24-30 Wh/kg, their overall efficiency is 0.8, and depth-of-discharge at 6,000 cycles is 0.6-0.8 (Graves, 1982). The Ni-Cd is a standard for comparison of secondary systems, while the Ni-H_2 battery is a hybrid between the secondary battery and the fuel cell on account of hydrogen being used instead of a secondary electrode. Ni-H_2 batteries were selected by NASA for free flying platforms because they are more reliable than fuel cells and 50% lighter than Ni-Cd batteries (Thomas, 1986). Pb-acid batteries have been the best developed of all vehicle batteries and are frequently favoured in terrestrial applications where cost plays a more important role than in space oriented systems, and where the load requirement must exceed 1W continuously.

Table 16.1. *Characteristics of batteries (Dindin, 1986)*

Battery Type	Energy Density (Wh/kg)	Power Density (W/kg)	No. of Deep Cycles
Improved lead-Acid	40-60	80-104	400-1000
Sodium-Sulphur	150	75-150	500-1000+
Aluminium-Air	400-500	150	N/A
Lithium-Iron Sulphide	80	120-140	500
Nickel-Zinc	80	120-140	500
Conductive Polymer	100	1,000	?
Zinc-Chloride	65	60	1500+
Zinc-Bromine	60-85	120-140	400+
Lithium-Molybdinum Disulphide	100-140	200	N/A
Lithium-Sulphur	200	400	500-1000

Flow Batteries

Flow batteries such as Zn-Cl and Zn-Br store reactants for one electrode in an external tank (Kordesch *et. al.*, 1985). The ultimate energy capacity of flow systems may be varied by maximising the tank size of the cathode reactant. Such batteries have been mass produced with energy contents up to 100 kWh at costs comparable to Pb-acid systems. Further advantages of flow batteries are their simple operation and ability to discharge without damage. Also, no trickle charging is required as flow batteries operate at fairly constant discharge and charge voltages; self discharge is negligible.

Fuel Cells

A fuel cell produces electricity by oxidation of a fuel, often hydrogen, and differs from other electrochemical cells in that the chemicals are stored separately and are supplied to the electrodes on demand. The fuel cell was the only electrical power source light enough, and compact enough, to provide the moon landing vehicle with its energy needs. It also provided drinking water. The simplest non-rechargeable primary fuel cell consists of supplies of gaseous oxygen and hydrogen brought together over catalytic electrodes (Figure 16.19(b)).

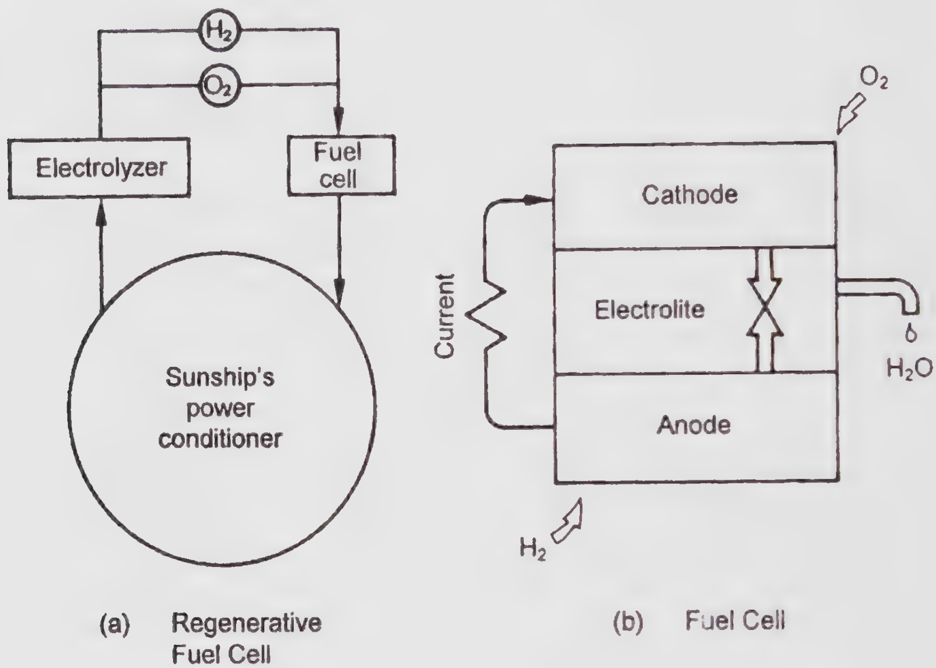


Figure 16.19. Simplified representation of a regenerative fuel cell. Oxygen may be obtained from air.

A rechargeable secondary fuel cell system, as required on airships, would also contain a separate electrolizer which uses the direct current produced by the solar cells to split water into oxygen and hydrogen (Figure 16.19(a)). Theoretically, secondary fuel cells can operate at a thermodynamic efficiency close to 100% (Britannica, 1974) although in practice much lower efficiencies have been achieved (Tucker, 1986). The efficiency of the H_2-O_2 fuel cell may decrease at low temperature in cold weather but during high power output, the cell temperature would rise, thereby increasing efficiency (Watson and Risser, 1985). Deep discharge up to 100% has no adverse effect on secondary cell performance (McBryar, 1980) and depth of discharge values of 90% can be expected (Graves, 1982). Fuel cells offer considerable flexibility because changes in energy storage requirements are easily accommodated by changing storage tank size. Fuel cells are also significantly lighter than batteries. They have higher specific energies which increase with increase in cell energy capacity and associated reactant weight (Table 16.2), since only the size of the various tanks in the system must increase to accommodate a longer discharge cycle. If oxygen is obtained from the air, then the size of the hydrogen tank would determine the energy content. The energy density of such a system could be about 2,640 Wh/cm^3 (Watson and Risser, 1985).

Both the weight and volume of fuel cells are critical for space applications, but in airships the weight of the cell is the more important parameter. NASA usually uses batteries when the required capacity is below 100 kWh, and fuel cells for larger systems (Hill, 1986). The scaling effect gives specific energies of 106-377 Wh/kg for discharge times of 4-16 hours and higher values of 660 Wh/kg are predicted (Graves, 1982). However, if a pressurised container system is used, the highest effective specific energy of 1,500 Wh/kg could be obtained with the H_2-O_2 fuel cell with Kevlar tanks (Watson and Risser, 1985). This would mean that only 133 kg would be required to store 200 kWhs of energy on the airship. An alternative Hydrogen-Chloride cell has an effective specific energy of 555 Wh/kg (Watson and Risser, 1985). Fuel cells can in principle be reliable, although NASA found batteries more reliable. Fuel cells are also quiet and require little maintenance since they contain few or no moving parts. The reaction product of the H_2-O_2 cell is non-polluting water.

Table 16.2. Effect of size of fuel cell on specific energy (Graves, 1982)

Storage capacity (hrs)	4	8	12	16
Specific energy (Wh/kg)	106	205	294	377

Fuel cells are classified according to their electrolyte. The Bacon cell uses an alkaline electrolyte and depends on clean fuels. Other developments depend on a phosphoric acid electrolyte intended to burn ‘dirty’ sources of hydrogen such as naphtha operating at 200°C; which is a cause for concern (Cross, 1986). Fuel cells must, however, meet four requirements when used with solar cells: (1) The cell reactants must be electro-regenerative; (2) the fuel cell must be scaleable to power needs; (3) the cell must operate with intermittent input and output power; and (4) the reactants must be transportable as liquid or gas. Considering these characteristics, only alkaline, acid, and solid-polymer electrolyte cells would appear feasible (Watson and Risser, 1985). Fuel cells using solid-polymers as electrolytes have potential advantages over phosphoric acid cells in that they are less corrosive, have higher current densities and are lighter (Chementator, 1986) (Milgrom, 1986).

Potentially, fuel cells offer several advantages in photovoltaic systems over batteries for energy storage: (1) higher values of depth-of-discharge; (2) higher energy per mass and volume; (3) no internal discharge with the reactants separated; (4) operating lifetime not limited by charge/discharge cycles; and (5) higher potential efficiencies (Watson and Risser, 1985).

Flywheels

Flywheels store energy in the form of kinetic energy of rotation and power can be provided in a fraction of a second if required. Flywheel rotors are housed in a partial vacuum to reduce the drag associated with the rotation speed which can vary from 2,000 rpm to over 35,000 rpm. Calculations indicate that, even without a partial vacuum, energy losses would be relatively small, implying a storage potential of several days or even weeks (Tucker, 1980). Frictional losses can be reduced by roller bearing suspension or by magnetic suspension using powerful rare earth magnets.

A motor would convert electrical energy from the solar cell arrays to mechanical energy which is stored in the rotor system. The same motor would act as generator to convert mechanical energy back into electricity when needed. Electronic switching permits a single unit to operate in both motor and generator modes. Efficiencies of flywheel systems of 87-90% can be expected, but these exclude losses associated with power conditioning (Graves, 1982).

The amount of energy that can be stored depends on the flywheel's density, and the strength of its material. The effective kinetic energy is related to the square of the rotational velocity. Internal stresses of a material with half the density but twice the strength of steel, will equal those of steel at twice the rotational speed. However, at the higher permitted rotational speed, its kinetic energy will be much higher than the steel equivalent.

Table 16.3. *Characteristics of two flywheel systems (Graves, 1982)*

Rotor Type	Titanium	Kevlar
Rated power (kW)	2.5	2.5
Stored energy (kWh)	1.5	1.0
Specific energy (Wh/kg)	19.5	31.5
Depth-of-discharge	0.75	0.75
Efficiency	87%	90%
Rotor speed (rpm)	35,000	37000

Improved rotor strength-to-weight ratios were obtained by using composite materials such as Kevlar (Renner-Smith, 1980). The failure criterion is based on fibre breakage at the centre of the rotor disc. Composite flywheel energy density is expected to be only about 80% of predicted values (Nimmer *et. al.*, 1980).

Flywheels are caged to avoid the substantial damage that would be caused by disruption of the rotor into a shower of high velocity fragments. Table 16.3 indicates rather low specific energies for flywheels even when using Kevlar, although higher values have been reported for large scale energy storage systems (Table 16.4). Other estimates give specific energies far in excess of 100 Wh/kg for carbon and silica glass fibres but particularly fused silica (Tucker, 1980). Flywheels have problems related to break-up at high speed, long-term energy loss, and relatively low specific energies.

Table 16.4. *Characteristics of different flywheel materials for large scale energy storage (CEGB, 1980)*

Material	Useful Energy (Wh/kg)
Carbon fibre/epoxy	51.5
E-glass fibre/epoxy	14.0
S-glass fibre/epoxy	19.6
Kevlar fibre/epoxy	76.2
Wood (birch)	5.8
Mild steel	8.2
Maranging steel	24.0
Titanium alloy	30.8

Comparison of Storage Systems

Based on the most optimistic expectations of performance and characteristics it appears that, for airship applications, the fuel cell may be preferable to the battery which in turn may be preferable to the flywheel. Fuel cells have by far the best specific energies of the three systems. Furthermore, an increase in energy storage can be achieved at a lower increase in cost for the fuel cell than for batteries as indicated in Figure 16.20. This is due to the fuel cell's non-modularity; a larger unit would have a considerably higher specific energy than a smaller unit (Table 16.2)

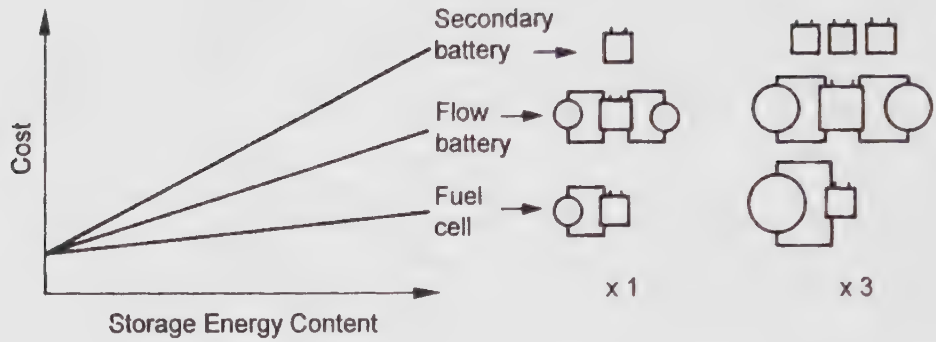


Figure 16.20. Relationship between cost and energy storage capacity of batteries and fuel cells with constant power requirements (Kordesch, 1985).

Weight Considerations

In airships, the solar power system would replace the fuel and engines of a conventional airship. The main components of the solar power system contributing to weight are the solar cells, collector grid system, the storage units, and the electric motors. The figures given in this section relate to an airship with length/diameter ratio of 3.48 and a lifting gas capacity of 22,000 m^3 (Khoury, 1986).

Low solar cell weight can be achieved by thin film technology. The weight of the deposited material could be in the order of 200 g/m^2 or even less. The collector grid network could add another 175 g/m^2. For a solar cell-collector grid system weighing 375 g/m^2 covering the whole surface area of the hull, the total weight will be 13% of total gross lift for a 5 tonne airship and reduces to 7.9% for the 22 tonne airship (Figures 16.21 and 16.23). These do not take into account the weight of seams, ballonets, or a separate envelope material. Weight reductions could be achieved through (a) an integral solar cell-envelope skin, (b) lower weight of the solar cells, (c) smaller coverage of the hull's surface by solar cells, and (d) operating the grid system at higher voltages.

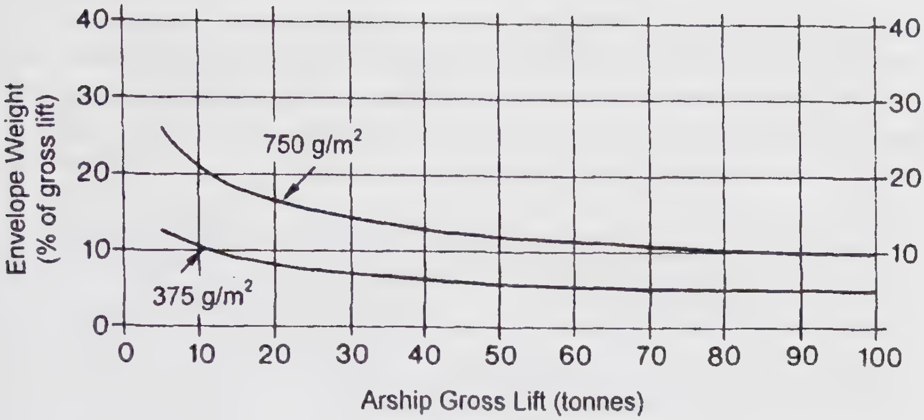


Figure 16.21. Envelope weight versus gross lift (l/d = 3.48) (Khoury, 1986).

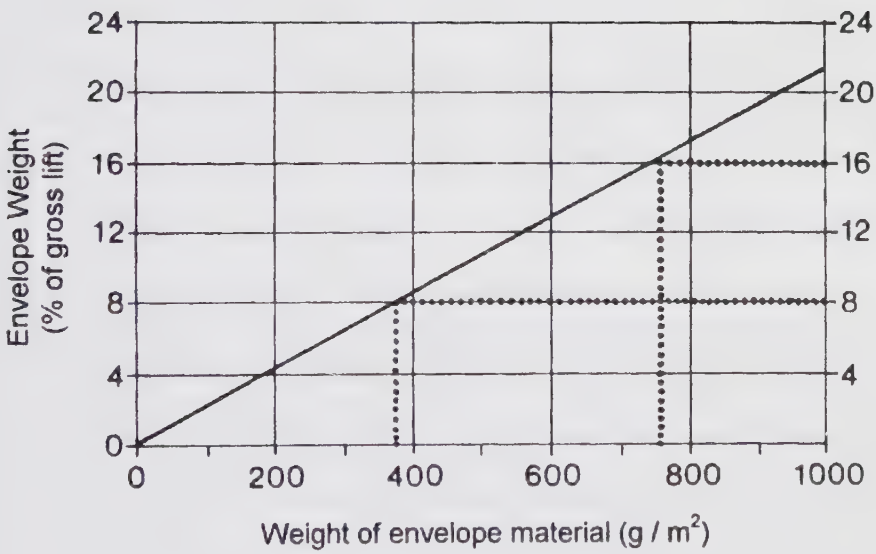


Figure 16.22. Effect of envelope material weight on the total envelope weight for an airship with length of 80m and diameter of 23 m (Khoury, 1986).

For the storage units, the key parameter is the energy density. The fuel cell has by far the best potential in this respect. For the specific energies given in Table 16.5, a 200 kWh fuel cell would weigh only 133 kg (0.6% of a 22 tonne airship) compared to 1,333 kg for the Sodium-Sulphur battery, and 2,632 kg for the Kevlar flywheel.

Table 16.5. *Potential energy densities of three types of storage units*

Storage Type	Energy Density (Wh/kg)
Kevlar Flywheel	76
Sodium-Sulphur Battery	150
Regenerative H_2-O_2 Fuel Cell (Pressurised Kevlar Fuel Container)	1,500

The use of brushless dc motors allows higher speeds to be attained. A four-fold increase in speed can result in a three-fold reduction in motor weight (Finch, 1986). A specific power of about 1.65 kW/kg can be expected when running at 9,000 rpm; this gives a weight of 121 kg for two 100 kW motors, representing 0.55% of the gross lift of a 22 tonne airship.

Potentially, the solar power system could weigh less than 10% of the gross lift of the 22 tonne airship and would then be competitive in weight with the conventional airship.

Cost Considerations

The solar-powered airship will have a higher capital cost and lower running costs than a conventional airship. Cost comparisons should, therefore, be made over the lifetime of the two types of airship in which the additional capital cost of the solar power system including interest is compared with the higher fuel costs of a conventional airship. When operating in remote areas and at high altitudes, however, supply of fuel for a conventional airship would be significantly dearer or not practically feasible. Direct cost comparisons can, therefore, only be made for certain and not all applications. Furthermore, it is generally expected that the prices of solar power systems would continue to fall, while prices of fossil fuels are expected to rise in the long-term.

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17

Roles and Economic Considerations

R. Hillsdon

INTRODUCTION

This chapter will advance the thesis that airships can never be economically viable unless their unique characteristics can be concentrated on specific roles, which demand these characteristics; it is self evident that such roles must be uneconomic for competing conventional aircraft.

Just as there are many types of conventional heavier-than-air aircraft adapted specifically to their roles, so there have been many types of airship - projected and realised - for their own perceived roles. It is a fact that there have been very few examples in history of airships operating commercially. While there are some obvious reasons for lack of commercially viable airships - notably the non-availability of helium for the first half of the century - it remains an enigma why this should be so. An inadequate appreciation of the correct type and size of airship applied to the various roles has been a major factor in the airship's lack of economic success. This chapter attempts an orderly analysis of the roles v. types v. market situation and discusses some primary cost parameters. Where military roles are considered, generalised 'cost effectiveness' substitutes for commercial viability.

THE UTILITY OF AIRSHIP TYPES

As mentioned in the introduction to this chapter, a large variety of airship types can be postulated. A thorough treatment of a large number of potential configurations was undertaken by Shaw, 1978 To contain this large variety to manageable proportions a different approach is adopted here, with airship types categorised according to the degree of augmentation of the lifting gas static lift by means of direct powered lift. The categories chosen are: A. No lift augmentation; B. Partial lift augmentation and C. Total lift augmentation.

Category A - No lift augmentation

This category comprises airships where the propulsion thrust line is non-variable and is fixed in a line parallel to the longitudinal axis of the hull. This configuration is common to, for example, most of the airships used in Royal Navy and US Navy operations during the two world wars and in post-1945 operations until the 1970s The only means of supplementing static gas lift to support initial heaviness at take-off or to counter lightness at landing was by using the aerodynamic controls to incline the body axis and so generate hull- lift, using airspeed. Such airships need a ground roll to achieve take-off or landing in positive or negative static equilibrium conditions. The category embraces airships with the hull so shaped as to improve the efficiency of generation of hull-lift.

Category B - Partial lift augmentation

In this category of airship the propulsion thrust line can be varied at will, usually about a horizontal transverse axis. This variation provides a vertical component of thrust, up and down, and avoids the need to change the incidence of the hull to control equilibrium excursions. The need for this configuration was appreciated and attempted very early in this century and used with some modest success in post first world war large rigid airship designs. Transmission technology, however, was not at a sufficiently advanced stage to allow reliability and it was not until the 1970s that viable designs appeared. The facility to vary the thrust line confers the ability to perform vertical take-off and landing and so permits a controlled hover and the pick up or set down of loads whilst airborne without ballast adjustment in zero ambient wind speeds.

Category C - Total lift augmentation

This category defines airships where the payload is totally supported by direct powered lift, i.e. where the gas-lift supports only the empty weight of the vehicle. In some design projects the thrust line may be varied in more than one axis or even in all axes.

To establish the possible utility of airships in these three categories the following discussion of their general characteristics is appropriate.

No lift augmentation

Category A produces what is without doubt the simplest and cheapest configuration of all and one that has given good service in the history of aviation. It is the category that includes the earliest controllable air vehicle: the Giffard airship of 1851. In the first world war the Royal Navy built and operated some 220 airships of this category (Abbot, 1989). They operated out of range of enemy interceptor aircraft and only two were lost to enemy action. Success in protecting UK coastal shipping against submarine attack was virtually total. The majority of losses were due to accidental or weather causes; even so the loss of life was remarkably small. In the second world war the US navy produced and operated a nearly similar total of number of airships on continental America from the tropics to the arctic. Again, success was total; no ships were lost from airship escorted convoys and only one airship was lost to enemy action - shot down by a surfaced submarine's gun when the airship had lost engine power. These exploits are recorded here appropriately because they must represent unequalled cost effectiveness of any weapon system in the history of war. In both cases the airship solution was forced upon the two navies - the British in world war one and the US in world war two - by the shortages of other resources, both material and manpower. In the US Navy's case the total lack of preparation for the threat of the submarine to coastal shipping also predicated an airship solution (Hoyt, 1978).

The basic characteristics of this category that contributed to successful wartime operation are the extreme endurance (the North Sea class airship NS1 completed a flight of 49 hours in 1917) and the ease and cheapness of production. Airspeeds, although low, were adequate to provide the margin over surface craft needed for operations. On the negative side, the poor control characteristics of the type must be held responsible for the high accidental attrition. Setting aside fire incidents, mostly resulting from the use of hydrogen, and propulsion unreliability, the accident statistics of both wars show that terminal phase, i.e. take-off, approach and landing incidents and mooring/ground handling incidents, were dominant. In the flight phases, relying solely on aerodynamic controls to alter the body axis to add or subtract increments of lift is an inherently unsatisfactory mechanism amounting to gross instability. As an example, take an airship of this category flying near the surface interface that suffers a vertical perturbation downwards owing to a gust or thermal change. To recover, the pilot must increase body lift, which he can do by either increasing airspeed or changing body incidence or both. Bearing in mind that response rates are slow for either option, increasing airspeed by applying extra thrust is safe only if the airship has retained a positive incidence. In the case of a downward perturbation it is likely that the airship will have assumed a negative incidence relative to the ground surface; increasing airspeed only increases risk of surface impact. If the other option of changing body incidence in the positive sense is chosen, the action of applying up-elevator angle is chosen, the first result is an increase in the downward force generated by the horizontal stabilisers, exacerbating the problem. In the ground phases, yaw perturbations become the main problem. With the weight of the tail surfaces, it is extremely difficult for the designer to achieve a weight distribution so that the main wheels are anywhere other than well aft of the lateral aerodynamic centre. The airship on wheels is thus very vulnerable to side gusts and, if unrestrained, can easily broach and be carried away downwind. Having to perform a ground roll in this parlous state is clearly a danger, bearing in mind that the aerodynamic centres are ineffective at low airspeeds.

The product of these various problems is an airship whose role effectiveness is very heavily limited by weather conditions during ground interface phases of operation.

Discussion with various regulatory authorities gives little hope of improvement in this respect and for civil operations certification seems likely to be restricted to low windspeeds in the order of 25 knots. There is also an apparent size limitation for airships in this category. Assuming only manual ground handling, the economics of ground personnel provision suggests an upper size limit of the order of 5000 cubic metres. While the provision of various assisting devices is a possibility, these increase first cost and maintenance cost and so tend to negate any gain.

Partial lift augmentation

Category B - This category represents a modest degree of complication and overcomes the low speed controllability to a large extent. Such airships - widely known today as 'vectored thrust' airships - seem to set a standard acceptable to certification authorities and examples of the type have been certificated by leading regulatory bodies up to a size of 10,000 cubic metres gross volume for passenger transport roles. The favourable 'square/cube' growth law, which governs displacement airships, provides weight margin for control enhancement devices such as bow or stern thrusters to assist in low speed yaw control. The vectorable thrust line permits very short or zero roll take-off and landing.

The degree of lift augmentation can, of course, be varied by design but the category cannot claim a true freight carrying capability, and exchange of ballast is necessary in any such role, where the scope of the payload is outside the design differential between maximum lightness and heaviness.

The modest weight penalty of a competently executed vectoring system preserves the key attribute of a simple airship, i.e. extreme endurance at patrol airspeeds, while largely eliminating the type of accident to which Category A ships were so prone.

The attributes of Category A and B airships have much similarity. In both categories the endurance and range characteristics are a direct function of the margin between maximum usable heaviness and lightness. The dynamic hull lift of both categories is of the same order for a given size so their capabilities in patrol roles are similar. The difference between the categories lies solely in the operability and safety, this difference becoming more marked as size increases.

Total lift augmentation

Category C - The objective of designs in this category, i.e. to support the payload by powered lift, leads inevitably to a high degree of complexity. It is worthwhile here to examine the three main approaches to generation of the powered lift, to illustrate the scale of the engineering effort involved.

The van Dusen project generated its powered lift by Magnus effect on a rotating spherical gas envelope. The envelope rotated about a pivot axis held between the free ends of a horseshoe shaped structure. The car was formed in the centre of the horseshoe beam and thus hung below the envelope. Propulsion and power for rotation was to be provided by engines at each end of the pivot axis. The project advanced to the stage of unmanned model trials but, so far as is known to the author has not progressed further.

The *Piasecki* project typifies several proposals of the late 1970s in which a traditionally shaped airship envelope supported laterally placed framework, which each supported a complete 555 helicopter rotor and dynamic system at each end. The four helicopter rotors were projected to give a total nett lift of some 25 tons. The prototype was destroyed in a crash during early flight tests in 1985 and the programme does not appear to have been resurrected.

The *Cyclocrane* project involved a novel and ambitious means of providing the powered lift. The complete envelope system was rotatable about a central axial beam. The ends of the beam supported cables by which the car was suspended below the envelope. Propulsive power and envelope rotation were provided by engines mounted at the ends of high aspect ratio wing-like blades radiating from the envelope's surface at its mid length. Each of these blades had at its end a further aerofoil placed normal to the blades span, in the manner of a 'Tee-tail'. Each complete blade could be controlled over a large pitch angle, giving force either parallel to the axis of the pivot beam (for longitudinal motion with no rotation) or ranging from 90° from that (giving zero axial force along the pivot beam but maximum rotation). Pitch of the 'Tee-tail' aerofoil could be controlled cycloidally to provide combinations of vertical and lateral force vectors. The prototype *Cyclocrane* flew in late 1985; it is understood to have demonstrated its design objective of a 2 ton lift. The full scale airship was to provide a 20 ton lift but the programme appears to have made no further progress.

Common characteristics of the three categories

The descriptions of these three concepts lead directly to identification of their common characteristic, namely a very high degree of complexity. This complexity was seen to be worthwhile, given the common objective: to provide a large payload, high manoeuvrability and operation costs well below that of a comparable helicopter. In short, the designs were aimed at the crane lift role. At least two of the designs were funded by forest industry agencies, for the extraction of high value timber from areas difficult for other means to access. The characteristics were thus biased towards relatively short range operations and towards roles where eliminating the need for ballast exchange is vital.

Categorisation according to hull rigidity

Before concluding this discussion on the utility of various types or categories, there is another well known categorisation commonly used for airships that should be considered, namely that of sorting by the type of hull structure, i.e. into rigid, semi-rigid or non-rigid airships. This means of categorisation has indeed been useful in the past, when material technology and the lack of analytical capability gave some validity to the method. It is the author's contention, however, that the advent of modern technology has blurred the original meanings of these definitions. Originally, that is until the 1930s, non-rigid airships were limited in size by practical difficulties of providing adequate hull bending strength to support the car. The upper limit of size (gross volume) was <400,000 cubic feet; represented by the British North Sea and Parseval classes. That volume, coincidentally, was the starting point for rigid airships, the Zeppelin LZ1 being quoted as having a volume of 400,000 cubic feet. By 1930, LZ127 had appeared at 4 million cubic feet and R100 and R101 were both over 5 million cubic feet. There was thus a significant discontinuity in the growth curve.

The situation has since changed in absolute terms with modern materials and techniques. There exists a reasonable consensus that a non-rigid design solution would apply at least up to 3.5 million cubic feet, using modern materials. Since no worked-up design for rigid airships of any comparable size has emerged, one must turn to another method to identify the magnitude of the growth discontinuity. In the author's paper the design of the US Navy airship at 2.5 million cubic feet was used to approximate an answer. In this design the pressurisation system (ballonets, trunks, valves, fans etc.) comprises a considerable weight, as does also the car suspension system (curtains, cables, load transfer mechanisms etc.). In a rigid airship these weights would be greatly reduced or disappear, although a membrane would still be needed to separate the lift gas from the surrounding air. The rigid airship, however, must have structures not required by a non-rigid. Postulating that a likely structural design for a modern rigid airship would be a semi-monocoque hull using sparse framework with a skin of rigid honeycomb material, it is possible to make a gross assumption that the framework, crew accommodation and systems in a rigid might approximate to the pressure system, suspension systems, crew accommodation of a non-rigid. That assumption would leave the major part of the weight as residing only in the hull skin. For the US Navy Airship the skin area is known - as is also the skin weight - at just under 13 ounces per square yard. If one contends that even the lightest practical honeycomb will weigh in the order of 0.5 pounds per square foot, so the skin for the same size rigid airship would be some 22 tons heavier than the non-rigid; a difference likely to dominate the crudity of the structural equivalence assumption.

As size grows, with a cube *v.* square law applying, the hull weight difference would diminish proportionally, possibly to a point where it is entirely absorbed. Projecting these approximations upward the author concludes that a non-rigid could be viable at least to 4 million cubic feet with only modest hull material development, while a rigid design does not appear viable below 6-7 million cubic feet. It is interesting to note that Sir Dennistoun Burney (1929), chairman of the company that built R100, presented cogent arguments that the airship was too small and would need to be virtually doubled in size to be efficient!

Main attributes offered by airships

In summary of this section, the attributes that can be demanded of an airship in performance of various roles can be listed and sorted to indicate how well the three chosen categories might be expected to realise the attributes. Just as the three categories were arbitrarily chosen, the assessments made below are generalised: they could be refined, of course, to consider specific types and actual figures of merit.

Such refinement is considered to be outside the scope of this work. Listing the main attributes offered by airships in general:

Very High Endurance

As the most sought after quality, some remarkable statistics appear. The first World War Coastal class at 170,000 cubic feet would be considered small compared with the Skyship 600 of 1984 at 235,000 cubic feet. Both types, on a normal patrol profile could easily achieve 24 hours endurance, while under favourable conditions both achieved 50 hours.

Speed

General statistics show a best cruise speed in then order of 25-35 knots with maximum between 55 and 80 knots, all speeds being size dependent.

Operating Altitude

Any airship must sacrifice gross volume to achieve altitude, thus a direct payload decrement occurs. In very rough order terms an airship required to take off at sea level and operate at 10,000 ft loses 25% of its lift gas volume; for 20,000 feet operation the volume loss rises to about 50%.

Crew and Equipment Environment

The low inertia forces and noise/vibration characteristics give a conventional airship a very good rating; some hybrids must be expected to be less acceptable.

Payload Volume

Structural weight considerations act in the airship's favour and space is very easy to provide. As a ratio with propulsion parameters it becomes excellent compared with conventional aircraft.

Operating Costs

Direct operating costs are very low. If manual ground handling is used, together with mobile operations, the costs escalate very rapidly.

Safety

Very few viable statistics exist for airships in non-military operations. The history of operations with hydrogen lifting gas is dominated by the highly publicised loss of the Hindenburg, so it seems to be forgotten that the ship had made over fifty commercial flights, including thirty-four ocean crossings. Put together with the operations of the two Graf Zeppelin airships, the statistics look much more favourable. While the total passenger-miles flown by these three airships is not available, a considerable figure was amassed. Hindenburg alone, in just a year had carried 2,800 passengers in a total of fifty-five flights and covered some 186,000 miles. These figures give something in the order of nine million passenger miles. With the only fatalities being the thirty-five in the Hindenburg, the rate must have compared well with the other contemporary aviation statistics.

Civil commercial operations with helium as the lift gas are relatively few; the major accident record, however, is extremely good, there being no known fatalities. It seems the modern airship is inherently a very safe vehicle.

External Signatures

Because of the low mass, low propulsion energy requirement and low structural density of airships, they can quite easily be designed to show very low external signatures. Radar, infra-red, acoustic, magnetic, gravitational and chemical emission signatures can all be reduced to low values.

Sensor Platform Capability

The airship has a proven historical capability as a platform for sensors. US Navy airships in World War II carried radar to search for surfaced U-boats. The huge ZPG2 and ZPG3 airships carried very large antennae, the 1.5 million cubic feet ZPG3W carrying a 40 ft. span antenna inside the envelope when performing its distant Early Warning (Dew line) function to provide a counter to the perceived trans-Arctic threat from Russian bombers. The fabric hull envelope of a non-rigid provides a natural radome and the low placement of the propellers minimises side lobe modulation. The very large sensors required for geographical survey are also quite easily mounted.

An assessment of how well the three design categories of airship display all the above attributes is made in Table 17.1.

THE SPECTRUM OF POTENTIAL ROLES

Over their history airships have led aviation developments in a number of special roles. The first World War saw airships in the roles of the first bombers and the first specialist anti-submarine patrol aircraft. Between the wars Europe saw the airship as the logical vehicle for intercontinental rapid passenger transport, while the USA envisaged them in a naval role as a hybrid of scouting cruiser and aircraft carrier. The increased capability of modern airships has led to a multitude of roles being proposed; in some cases actually performed. To achieve some rational presentation of these many roles, they are broken down here as follows:

Civil Roles	Passenger Transport Freight Transport Crane Lift Promotional Camera Sightseeing Leisure Skylab Survey
Civil Power Roles	Police Customs/Immigration Area Control Search and Rescue
Para-Military Roles	Coastguard Fishery Protection/Anti Piracy Counter Insurrection/Terrorism Sovereignty Enforcement
Military Roles	Airborne Early Warning (AEW) Anti-Submarine Warfare (ASW) Mine Countermeasures (MCM) Command, Control, Communication and Information (C3I) Reconnaissance, intelligence, surveillance and target acquisition (RISTA)

The list is not exhaustive and some of the sub-roles may be interchanged between broad headings, *e.g.* area control could describe a role applicable to all four broad headings. Some brief description of all these roles is given below, with commentary on the suitability of airships in general and of the three lift-augmentation categories in particular, to undertake the role.

Table 17.1. *Assessment of the capability of three airship design concept categories to realise general airship attributes*

ATTRIBUTE	Category A No Lift Augmentation	Catergory B Partial Lift Augmentation	Catergory C Total Lift Augmentation
Endurance	*****	*****	**
Speed	**	**	**
Altitude	*	*	*
Internal Environment	****	****	**
Payload Volume	****	****	**** (External)
Operating Costs	****	****	**
Safety	***	*****	***
Signatures	****	****	**
Sensor Platform Capability	*****	*****	-

Key: **** Excellent   **** Very Good   *** Good
** Fair   * Poor   - Unacceptable

Civil Roles

Civil Passenger Transport

This is the role for which the early visionaries saw the airship as suited. If this vision seems incredible now, it must be remembered that Count Zeppelin's first creation - a veritable monster over 400 feet in length - took to the air and flew for eighteen minutes some three years before the Wright brothers first flight was measured in seconds and yards. By 1909, the year of Bleriot's English Channel crossing, Count Zeppelin was forming an airline and starting passenger carriage between major German cities, operations which were continued until the impending war usurped all attention. Post war, even with all the impetus given to aeroplane development, the airship still appeared the logical choice for long range travel. Just a few weeks after the first West to East Atlantic crossing by Alcock and Brown, the R34 airship took off from Edinburgh and, with a full crew, a stowaway and a ship's cat, flew uneventfully to Mineola, Long Island, returning later to England with similar serenity. It is not surprising that passenger transport by airship became such an obsession in the 1920s.

Disregarding all the other factors, however, which prevented the role's coming to maturity, the advent of reliable conventional passenger aeroplanes soon showed up the flaw in the airship's aspiration to this role. All mass transport systems operate on a 'round trip' basis; logic decrees that this must be so or the disposition of assets would become unacceptable. For a fixed wing aircraft, with a healthy margin of cruise speed over prevailing winds, differences in the elapsed time between out and return journeys are acceptable and can usually be absorbed in the turn round ground times. For the airship, however, with a limited cruise speed, any scheduling model breaks down against quite modest head winds, with a 'pile-up' of ships at the down-wind base. Since airships cannot just be chocked and parked but require a substantial investment in a safe mooring facility for each ship, the characteristics of an airship do not support scheduled passenger carriage. Exceptions may of course occur in niche markets, such as areas of poor surface infrastructure and isolated communities and/or where low flight frequency and irregularity is thus acceptable. These conditions may apply, for example, in tundra or archipelago regions. An airship can show an unexpected advantage when operating in low infrastructure regions, particularly where diversion landing sites are not available, by using its endurance to 'wait out' temporary bad weather conditions.

Freight Transport

Much the same considerations apply to this role as to passenger transport; there are two factors which create extra differences for the airship in attempting to achieve high productivity. Firstly, unlike the two-way flow of passengers, a significant proportion of freight traffic is one way only, leaving a problem of ballast exchange. Secondly, there appears to be a limited range of cargo which might form a market niche for the airship. Low density goods would seem suitable, but flight speeds over long stages would preclude perishable items unless the weight penalty of refrigerated space was acceptable; such a weight penalty would reduce the margin of productivity over fast surface transport. In general it is not easy to see significant applications for airships in this role, with the exception of low infrastructure routes as discussed under passenger transport.

Crane Lift

This role is a special case of freight transport. The crane lift requirements of today are largely met by the helicopter, with aircraft in the heavy lift class of the CH47 (Chinook) and the CH53 (Sea Stallion) capable of carrying external payloads of 32,000lb. It is of interest, however, that the small scale civil crane lift operations by helicopters all use helicopters that are derivatives of military designs, i.e. where the huge development costs have been borne by military budgets. Self evidently, the role requires an extremely accurate hover, with high control power in all axes. This requirement is, of course, the driver for the Category C designs, which aim to provide the required manoeuvre power while eliminating the need for ballast exchange, inimical to the crane role.

Promotional, Camera and Sightseeing

These roles are taken together since they have much in common; indeed it is not usual for all three functions to be performed simultaneously. There are many historical examples: perhaps one of the earliest being promoting the cause of the suffragettes in 1909. The airship hull provides a natural billboard, nowadays augmented by high technology computerised illuminated signs for night work, which can replay a video tape. The inherent safety of the airship convinces most authorities that operations are acceptable over large conurbation's and sporting gatherings; in recent years the presence of the airship over Olympic events has become commonplace. The ubiquitous 'Goodyear Blimp' pioneered the use of the airship as a stable and long endurance camera platform over major events. Airworthiness certification under modern codes has permitted the combination of revenue passenger carriage for sightseeing with promotional work.

Leisure

This role is covered separately since it comprises more than simple sightseeing. Looking back at the inter-war operations of the large German airships, there seems little doubt that the majority of passengers sought the novelty of an airborne cruise liner rather than a routine method of travel. Given the development of competent airships this role must have the potential to re-emerge in a serious manner. While all cruise ship operations have a large element of sightseeing, the primary motivation is that of travel in style and comfort; isolated from the tribulations of other mass transport systems. The destinations of ocean cruise liners are necessarily limited, the airship could overcome a surface ship's limitations and open up the world's many inland tourist areas with travel in cruise liner comfort.

One other aspect of the leisure activity to be remembered: that is as a personal sport, hobby or ambition. The growth of hot air ballooning as a significant sport has shown that people with money available to fund their ambitions are likely to be persuaded to invest in a personal challenge. In the very early days of airship history Santos Dumont is reputed to have built his airships purely for the sheer fun of it. That the spirit persists today is shown by the pedal powered 'White Dwarf' airship (Allen, 1988). This one man airship is stated as requiring only 1200 'work hours' to build and would appear to be suitable for kit form construction. This airship established two new world records in the Gas-Airship category (BA-1-10) with a flight of 58 miles. The ship could be transported, when deflated, in a light trailer.

'Skylab'

A small sector role exists for the airship in performing airborne measurements for civil research purposes. Investigation of low level atmospheric phenomena and unintrusive investigation of natural history subjects are two examples of many research aspects for which airships have been used in recent years; there are clearly many other potential applications.

Survey

This role embraces all aspects of conservation, investigation and exploitation of resources. Obvious examples are geophysical survey, hydrographic and cartographic work, wildlife survey and archaeological survey. While these roles can be and have been performed by heavier than air aircraft, the endurance, benign environment, safety and low self-signatures of the airship - particularly the ability to fly slowly and safely at low altitudes - give the airship a very strong potential in these roles. Also included under this heading is the role of calibration. Many ground radars need initial and repeat calibration and the ability of an airship to perform this task cost effectively has been positively established.

Civil Power Roles

These roles comprise assistance to government agencies whose obligations are the exertion of national internal laws, regulations and policies, ranging from enforcement through assistance to citizens.

Police/Customs and Immigration

Airborne surveillance has come to be accepted as a necessity by the agencies of enforcement in these fields. All countries have coastal or land borders where illegal penetration prevention is essential to national policy; similarly the policing of both urban and rural areas is an onerous task. These functions are much enhanced by the improvement of line of sight visibility given by an overhead platform and the airship provides an ideal vehicle for the work. With state of the art optical and imaging devices miscreants and their vehicles can be identified at very long ranges allowing an airship to increase the effectiveness of ground units. Unlike helicopters and fixed wing aircraft, the airship is safe and unobtrusive for operation over populous areas: unobtrusive because people on the ground become used to seeing airships in a promotional role and need not be aware of policing authority personnel aboard. It was in this manner that the Los Angeles Police Department maintained covert surveillance of the 1984 Olympics from an airship doubling in the promotional role.

Area Control

This role is a broadening of policing type operations to an airborne command and control role co-ordinating various agencies' actions in the event of major surface problems. Flood, earthquake, oil spill, forest fires, accidental release of toxic threats etc. all have one factor in common: surface communications are impeded. A long endurance airborne vehicle, with the capability of maintaining 24 hour cover, plus the ability to hover or touch-down to pick up or emplace surface assets has an obvious application. The control of scenes of widespread civil commotion is area control applied to a policing function.

Search and Rescue

The limitations of conventional aircraft are all too often revealed in search and rescue operations. While helicopters and fixed wing aircraft perform nobly, they are both very expensive assets to wield and they do not provide an ideal search platform. A controlled experiment by US Coastguard in 1983 used a small airship to measure visual search effectiveness for comparison with both helicopters and fixed wing aircraft. The report concluded, 'It (the airship) provided good visibility, a comfortable crew environment, relatively long on-scene endurance, a low altitude capability and a modest range of search speeds. Detection data collected during searches for persons-in-the-water indicated that the airship is potentially better than current USCG platforms for this mission'. The same evaluation also demonstrated an airship survivor recovery by rescue winch and the air to surface deployment of a semi-inflatable rescue boat; the latter capability being unique to the airship.

Para-military Roles

These roles are performed by agencies other than regular defence forces. The precise function varies according to the constitution of the countries concerned: in most cases these units will be armed.

Coastguard

Coastguard forces have a variety of functions of which the generic name is descriptive. These functions include, *inter alia,* management of coastal shipping, assistance to customs and immigration enforcement, support of hydrographic and navigational facilities, enforcement of seaworthiness regulations, search and rescue implementation and assistance in the event of maritime disaster. Of significance to the airship is that all these roles involve the maintenance of standing surveillance patrols.

Standing patrols are inherently expensive in personnel and equipment resources. The limited visual and sensor search ranges of surface vessels creates the need for an air component for operational efficiency. At least a twin-engine aircraft is essential for safety; a light fixed wing aircraft in this category is relatively low first cost but the range and endurance characteristics are poor: a scheduling model must be expected to show that at least two serviceable aircraft are needed to maintain a standing patrol, *i.e.* three are needed to allow for downtime. Crew-rest while airborne is not satisfactory, i.e. at least three crews are needed. A heavy aircraft is more capable for extended off-shore operation but first cost and operating costs are greatly escalated and the increased patrol speed causes lower search efficiency.

Even a small airship changes the equation dramatically. With extreme endurance at patrol speeds also comes the benefit of a sufficiently good on-board environment to allow effective crew rest; a 1990 demonstration of over 50 hours endurance included crew performance monitoring by a UK Civil Aviation Authority pilot to validate efficiency. Unlike conventional aircraft counterparts, the airship has the ability for direct interdiction by means of a boarding boat.

The conclusion that airships have potential in this role was established in the Final Report of the US Naval Air Warfare Development Center, which stated, 'Serious consideration of airships in maritime roles can be technically substantiated.'

Fishery Protection/Anti Piracy

These roles can be considered as specially focused variants of the coastguard role. Both require the ability to maintain over water standing patrols over long periods; both may require patrol either in near coastal waters or at considerable distances off shore. Interdiction capability is required. The rationale for airships is similar to that for the coastguard role.

Counter Insurrection/Terrorism

These roles are an extension of civil policing and area control roles, with an increased level of detection capability and armed force application required. The same rationale for airships applies in all these roles.

Sovereignty Enforcement

This role embraces all aspects of protection of national interests in territorial waters and Economic Exclusion Zones (EEZ). An airship's role would again be seen as complementary to other surface and air asset activity. Again the rationale for airships is similar to that for the coastguard role. An interesting facet of recent history is that this role was performed in the South Atlantic by HMS Endurance, which ship, with her helicopters, provided the required surface and air components. This ship was absent from her patrol area in early 1982 owing to budgetary constraints; a fact held by many commentators to have been a major factor in sparking the Falklands incident. The same components could have been exerted by capable airships (had they been available) based in the Falklands and South Georgia at a fraction of the cost of surface ships.

Military Roles

These comprise roles customarily performed by the constituted armed forces of a nation or alliance. The role headings chosen are those for which the airship is considered suitable, the criteria for suitability being actual demonstrated performance or credible study/analysis. All such roles change with the passage of time as various scenarios and technologies change and advance. The best known example of such change is seen in the history of the German Zeppelin force in the 1914-18 war. German army Zeppelins were first used for battlefield reconnaissance but losses to newly introduced high angle artillery soon became unacceptable. Naval Zeppelins were thought to have good potential for fleet reconnaissance but results were at best inconclusive, for a variety of reasons: weather, poor navigation and unreliability being chief among them. They made no contribution to the result of the Battle of Jutland.

Both arms then concentrated on the incendiary ammunition and the increase in operating altitudes of fighter aeroplanes quickly brought unacceptable losses and the campaign fizzled out. Since that time no airship has operated in wartime outside the cover of total air superiority; hence the criteria stated above.

Changes of threat and counter will continue; the four chosen roles considered all seem to have been relatively stable over at least a decade and there is some reason to think that they will remain so.

Airborne Early Warning (AEW)

This role is necessary because of the limitation to line-of-sight sensor range owing to the curvature of the Earth's surface. With any approaching threat, at whatever speed of approach, the earlier detection is made, the longer the time available for countermeasures. Detection range of a radar is a function of transmitted power and antenna aperture. The phased array radar of the US Navy Aegis equipped ships has tremendous transmitter power but, since it is placed close to sea level, its line-of-sight radar horizon is extremely short; thus its protection is vulnerable to a low altitude cruise missile - a 'sea skimmer'. British and US Navy losses to 'Exocet' missiles illustrated the point dramatically. Given that the speeds of such missiles can be raised from the subsonic to the order of Mach 3, the need for permanent AEW is obvious.

Airborne AEW is exemplified today by the NATO E3 'Sentry' aircraft as a land based system or the US Navy E2c 'Hawkeye' carrier based aircraft. Both of these systems necessarily carry their antenna externally, exposed to the airstream. To keep air loads to a tractable value, the thickness of the antenna housings are limited, the E3 antenna probably approaching a practical limit of size. The unfortunate radar designer, however, requires aperture size in both horizontal and vertical direction. If limited in depth, in simplistic terms, he must compensate in transmitter power - increasingly difficult for an airborne system. The smaller (in signature terms) and the faster the threat missile, the worse the situation becomes, since the frequencies required for optimum detection demand even greater aperture sizes.

A further factor is the relatively limited endurance of these aircraft, which causes a multiplication of the very large system unit cost to maintain round the clock cover. For protection of a naval force too, the options are limited. Either a fleet carrier unit must be provided at huge cost for each surface formation or, using land based aircraft, a further cost multiplier occurs, owing to the 'dead time' of transit to and from the operation zone. The role requirements therefore emerge as:

- Ability to mount a very large aperture antenna.
- Good environment for crew and equipment.
- Extremely long endurance.
- Only sufficient speed needed to remain over the scene of operations.

These requirements are well met by airship attributes and it is understandable that the US Navy turned to an airship design in the US Navy programme. A contract was let for design of an Operational Demonstrator Model airship in 1987 and a preliminary design defined a 2.5 million cubic foot non-rigid Category B airship.

The programme has suffered its share of funding difficulties but is still being funded. The delay is not all loss because no suitable radar has yet been defined; radar developments of this nature being much more complex than the basic vehicle development. The specified endurance for the airship required up to 30 days endurance, surface to air refuelling from its parent fleet at intervals of around two days. Vulnerability of the airship to enemy action was not at issue, since its radar capability would allow its parent fleet to defend it.

Anti-Submarine Warfare (ASW)

An airship in this role would be envisaged as complementary to other existing assets rather than having an autonomous capability. Various trials and studies have shown airship capability to:

- Tow submerged sonar carrying bodies, including line towed arrays. In this mode the speed of relocation between slow speed listening positions is a potential major asset.
- Deploy stationary tethered sensor arrays.
- Deploy and monitor sonobuoy barrier or search patterns.

Given initial development of a large platform, there seems potential for ASW variants, making use of the economy offered by the airship's excellent endurance.

Mine Countermeasures (MCM)

It is not widely known that airships were used in this role during the 1939-45 war. Following the clearance of axis forces from North Africa, airships were deployed from Port Lyautey in Morocco, having flown from the Atlantic in stages to reach the scene. Their task was to search visually for mines in the Gibraltar straits area. It is reputed that they were successful in this role because of the relatively clear water conditions. Recent examples of mining operations using traditional contact mines have shown that these antique weapons can still pose a difficult threat and be very onerous in the use of assets to counter. Modern technology has brought great sophistication to the mine. Magnetic, acoustic and pressure sensing or combinations of these can be used in conjunction with numerous devices to prevent the mines from being successfully swept; they can be programmed to ignore false signals or to change functional mode as required.

The biggest difficulty in the clearance of channels for access to and from harbours and anchorages; bottom laid mines for use in such areas must be distinguished from natural or man made detritus. A system to deal with bottom laid mines must first positively identify and map all suspicious objects in the subject area. While shallow water divers can perform the task, the risk to life has led to the use of robot underwater vehicles for the identification, plotting and neutralising function, the robot vehicles being connected to a parent vehicle by umbilical cables to transfer data. The vulnerability is thus transferred to the parent platform; if this is a surface vehicle the risk of damage or loss is high. The task is time consuming and repetitive, a factor weighing heavily against the use of helicopters as parent platforms, because of their high operating cost; as does the fact that the task would comprise a high proportion of time spent in the hover - a helicopter's most vulnerable flight phase. Studies have therefore been made of the potential of airships to perform the role, with most promising results. Relatively small airships of design category B can perform the task adequately but no practical demonstration appears to have been performed: peacetime budgetary constraints creating an ultra conservative preference for traditional assets.

Command, Control, Communications, Intelligence (C3I)

The role is the military equivalent of area control in the Civil Power Field. In a naval environment it would probably be combined with AEW or ASW in a large oceanic airship. In an air superiority environment there is some potential for its use over land operations for co-ordination purposes; possibly in a smaller airship.

ROLE SUITABILITY

Having tabulated in Table 17.1 the extent to which the three design categories of airship realised general airship attributes and discussed the roles for which airships should have potential, this section makes a brief commentary on the role suitability of the categories and tabulates a subjective assessment of the suitabilities in tables grouped under the headings of the four main role groupings (Tables 17.2-17.5). Only suitability is taken into account, i.e. no consideration is given to market forces at this stage.

Civil Roles

Passenger Transport

Category A is rated less suitable than small Category B ships on grounds of safety. Large Category B ships will encounter ballast exchange problems, while Category C designs, as known at present, are not designed for the role.

Freight

Only Category C is seen as having potential in this role; for external freight. Ballast exchange problems in terminal operations weigh heavily against other categories.

Crane Lift

Only Category C designs have serious potential in this role, the high accuracy of hover control required being the dominant factor.

Promotional, Camera and Sightseeing

All operating experience points to the small airship as being most suitable to meet specific role requirements.

Leisure

Only Category C appears inherently unsuitable, while the requirements of 'cruise ship' operations are heavily in favour of large airships.

Skylab

All known requirements to date have been satisfactorily performed by small airships.

Survey

Category A are rated unsuitable because of their hover limitations in low ambient winds; Category C on grounds of range and endurance. Small Category B are capable of carrying all known sensors individually while large Category B could carry and deploy multiple sensors.

Table 17.2. *Assessment of the suitability or three airship design concept categories to perform civil roles*

Civil Roles	Category A	Category B		Category C
		Small	Large	
Passenger	**	***	**	*
Freight	*	*	*	**
Crane Lift	*	*	*	***
Promotional, Camera & Sightseeing	**	***	*	*
Leisure	**	**	***	*
Skylab	**	***	*	*
Survey	*	***	***	*

Key: *** Most Suitable ** Moderately Suitable * Unsuitable

Table 17.3. *Assessment of the suitability of three airship design categories to perform civil power roles*

Civil Power Roles	Category A	Category B		Category C
		Small	Large	
Police	*	***	*	*
Customs/Immigration	*	***	*	*
Area Control	*	***	*	*
Search and Rescue	*	***	*	*

Key: *** Most Suitable ** Moderately Suitable * Unsuitable

Civil Power Roles

The highly regionalised nature of all these roles is wholly in favour of small airships, which provide the required attributes adequately. Safety of operation in confined spaces is seen as ruling out Category A, since it is presumed the ships would have to operate from sites of opportunity.

Para-Military Roles

Coast-Guard

The demands of the role for interdiction and extreme endurance make Categories A and C unsuitable. Both Category B sizes, however, show suitability, the choice depending on specific tasking of the organisation concerned.

Fishery Protection/Anti Piracy

Considerations as for Coastguard mostly apply, with larger sea areas concerned favouring large airships.

Counter Insurgency/ Terrorism

Again the Coastguard considerations apply but the mostly overland nature of operations favours small airships.

Table 17.4. *Assessment of the suitability of three airship design concept categories to perform para-military roles*

Para-Military Roles	Category A	Category B		Category C
		Small	Large	
Coastguard	*	***	***	*
Fishery Protection/ Anti-Piracy	*	**	***	*
Counter Insurrection/ Terrorism	*	***		*
Sovereignty Enforcement	*	**	***	

Key: *** Most Suitable ** Moderately Suitable * Unsuitable

Sovereignty Enforcement

Interdiction and extreme endurance are paramount, while the extent of national borders or, for littoral nations, economic exclusion zones, favours large airships.

Table 17.5. *Assessment of the suitability of three airship design concepts to perform military roles*

Military Roles	Category A	Category B		Category C
		Small	Large	
Airborne Early Warning (AEW)	*	**	***	*
Anti-Submarine Warfare (ASW)	*	*	***	*
Mine Counter-measures (MCM)	*	***	*	*
Command, Control, Communications, Intelligence (C3I)	*	**	***	*

Key: *** Most Suitable ** Moderately Suitable * Unsuitable

THE POTENTIAL MARKET

Historically, the only occasions when airships have been used in large numbers have been times of war. Some 200 airships were accepted into service during the first World War and a nearly similar number during the second World War. Compared with these figures, the numbers produced in times of peace are trivial. There are a multitude of reasons for the disparity, many of which have disappeared with the passage of time; this means that one can eliminate many of the factors and study the period from 1950 to the present day. In this period the availability of the safe lifting gas helium has become widespread and efficient man-made materials to contain it have also been developed. Safety and lift gas cost have, therefore, ceased to be factors. In the same period technology has improved to the point where the analysis of design loads and stresses no longer present the problems that led to the disturbing frequency of structural failures in earlier decades. Meteorological knowledge has also developed, so the severe weather difficulties, which earlier airships encountered, are much reduced. One must look to other factors to see how favour has turned away from the airship. Focusing only on how factual or perceived factors have differed between airships and other types of aircraft, the following groupings of reasons occur.

Public Perception

The first airship, the Giffard design of 1851, so far preceded the first heavier than air aircraft that the public received some preconditioning. Ballooning became commonplace. The advent of Count Zeppelin's airship gave the public a conception that airships were the real future of aircraft; the rapturous reception of R100 after her transatlantic flight to Canada illustrates very well the prevailing public perception. This perception was shattered by the disasters to R101 and Hindenburg, which received the full attention of newly developed instant media coverage; in the USA, in particular, these disasters reawakened memories of the long trail of similar accidents - R38, Shenandoah, Akron and Macon - which put paid to pre-war airship endeavour.

The 1939-45 war saw such advancement in conventional aircraft that it was not surprising that in the post-war years all attention was directed their way. Few were aware of the almost incredible role efficiency of US Navy airships during the war. Further rapid advances: jet engines, competent helicopters and the like, left airships in total shadow.

Exaggerated Aspirations for Conventional Aircraft

With the publicity given to wartime aeronautical achievements and with universal availability of practical air transport post war, it was probably natural that conventional aircraft should be seen as a panacea, to be adapted to perform all aerial work roles, however inappropriate. As an example, it seems almost incredible that huge sums of money were spend in the 1950s and early 1960s developing helicopters for anti-submarine work, where their endurance in some cases was measurable only in minutes and attrition rates owing to unreliability were very high. In the same period US Navy trials were demonstrating far superior attributes for the role. The arguments can be applied to many of the civil and military roles discussed above. Like climbing mountains 'because they are there', the heavier-than-air aircraft seems to have been proposed for all roles because they existed. Only the advent of roles such as AEW against low flying missiles has forced reconsideration of airships.

Regulation

In the post war years, the rapid growth of air transport saw a natural and necessary parallel growth in regulations governing the industry, including great advancements and international co-ordination of airworthiness codes. While these regulations progressed in sophistication and scope, the lack of airship activity produced no demand for inclusion of airship codes, with the result that none had been produced. Pre-war, knowledge was not adequate to define the airworthiness cases accurately; a lack evinced by serious and sometimes catastrophic failures of structural elements of large rigid airships, involving main framework, tail framework and the exterior covering of both. The non-rigid had a better history; probably because of the compliant nature of the structure. Non-rigids, however, were not totally immune, a disastrous failure of a non-rigid airship's hull envelope occurring as late as the early 1960s.

This then was the background facing any attempt to reintroduce airships: no valid airworthiness code existed and the research necessary to produce valid code had been neglected. Britain was the first country to attempt a remedy. In response to proposals from the gifted designer, Roger Munk, the UK Civil Aviation Authority produced a new section of British Civil Airworthiness Requirements (BCAR) in the late 1970s. That work allowed a small degree of market penetration by Munk's designs and in response to the market, the USA, Japan and Australia published airworthiness codes in the 1980s. With the airworthiness problem advancing to solution, however, there remained and remains a problem influential against large market penetration, i.e. the operational regulations. No special case has been made for the airship; it has been 'shoe-horned' into the framework of regulation evolved for conventional aircraft - in a number of cases inappropriately.

An airship constructor attempting to market his product must face this problem and the total lack of operational infrastructure: no commercial flying or engineering schools, no common ground facilities and no reservoir of expertise in any field.

These three factors, *inter alia*, produce formidable difficulties in estimating the potential market and of achieving initial market penetration. The customer reaction is that displayed toward any new product, i.e. he does not know anything about the product, he may have false perceptions about it, he has an extant product, which appears to him to do the job (even if inefficiently) and has to face considerable difficulty in getting the new product into operation. Spyrou (1992) describes the problems graphically and from real experience.

The above factors create a very real difficulty in performing any valid market potential. For the purpose here, a methodology will be postulated by which a total market assessment could be made; with the caution that, as for any new product, market research will be a major expense.

For simplicity, let us take a role from the above analysis within the scope of airships known to exist and for which current vehicles show deficiencies. The chosen role that fits the description is *mine countermeasures, MCM.* The following steps - not necessarily taken consecutively - will be needed to perform any analysis of market potential.

Learning the Technology

It will be necessary to have, or to contract in, personnel with a detailed knowledge of MCM technology. Any personnel so engaged will have to interact with airship technology expertise to explore capabilities. An analysis of all equipment that could be deployed by an airship will have to be performed and a short-list of such equipment created.

Let us suppose, as seems likely, that a potential solution was for the airship to deploy a robotic underwater vehicle. Weights, power needs, control and navigation needs must all be identified and system requirements for data transfer, analysic display and recording analysed. The airship interfaces can then be described; in particular any performance and controllability improvement deemed necessary for the airship platform.

Operational Analysis

Given a set of solutions or, if fortune smiles, a simple solution, an operational analysis will need to be performed for various scenarios in order to predict the system(s) and compare effectiveness with known extant systems. An obstacle to this work exists to this phase with all roles: commercial security will protect data on all systems and in our chosen field, military security constraints will be operative. If, or when these obstacles are overcome, the output of this step may well be an iteration in the characteristics of both the airship platform and the deployed equipment.

Suppose that in this example the platform characteristics identified a need to increase the lift (size) and low airspeed controllability of the airship. The modifications would have to be designed and the cost of manufacture, development, test and trial/certification estimated. The same would apply if changes to the MCM equipment were seen as necessary; in this case the supplier would have to be persuaded or contracted to cost the changes.

The output of these two preliminary stages would be a design definition, costing and effectiveness definition of the proposed overall system.

Market Analysis

Armed with the output of the preceding steps, a comparison must be made with existing assets in the field. Basic data are available from defence publications, catalogues, journals and the like. Currently, of course, these data sources will reveal only surface units, with the exception of the USA, where helicopter towed sweeps are used. Since world supplies are limited to a few advanced countries, study of those countries' defence budgets may not yield information on the global costs of this specialist endeavour. The characteristics of the available systems can also be deduced and the systems cost effectiveness can be roughly estimated. If sufficient data are forthcoming it can be used for comparison with the airship system.

Demonstration

Before approaching the target customers identified as above with the claim 'we can sell you a cheaper and more effective system,' credibility must be established by some form of demonstration. A difficult choice must be made here. It seems obvious that the lead customer should be a technologically advanced country, with a national strategic interest in MCM. The USA would seem to qualify on both counts, with relatively few major maritime trade terminals, each of which could be subject to disruption by mining. Recent years have also shown very clearly that the US Navy has deficiencies in implementing the MCM role. It is here that one discovers the paradox, which leads to pronounced resistance to change in such countries. If deficiencies are shown in a defence capability of the nation, it follows that the defence staff specialist communities have been involved in procurement of the assets; they may well be less than enthusiastic about a demonstration, which might measure the deficiencies with stark clarity - far less so in funding such a demonstration. It may be far more effective to select a lead customer country with perhaps a lower degree of national wealth and, therefore, more inclination to be pragmatic about cost effective innovation.

Aimed Marketing

With an analysis of the cost effectiveness of the proposed airship system, and of the world customer community needs, the phase of active aimed marketing can begin. It seems trite to point out that market penetration will be slow, owing to the inevitable length of procurement cycles and the lack of extant airship infrastructure in most countries. Aim must obviously be directed at countries where existing assets are obsolescent or obsolete; even so, market penetration will be slow, arduous and expensive to achieve. This slow development of the market leads to equally slow development of sales or lease revenue to sustain the constructor's enterprise.

AIRSHIP ECONOMICS

This final section of the chapter attempts the vexed subject of the economics of the airship. It is a difficult subject for any high technology endeavour (airships today qualify for that epithet) but for the airship we again find a startling paradox: in the two world wars there can be little doubt that the airship provided a remarkably cost-effective solution to a very difficult problem, while in peacetime one can find little or no evidence of airships being economic in terms of life cycle cost versus total revenue. Any student of airship economics is recommended to indulge in the tutorial given in Norway (1954), which describes the vicissitudes of both the large airship (in the heyday of their existence) and of the 1930s conventional aircraft industry.

There is no record of Count Zeppelin's ever making a peacetime profit from airships. Useful case studies of peacetime airship economics are almost non-existent and most enterprises have managed to produce only single airships or very small numbers.

By far the largest batch production of airships has occurred in wartime, perhaps the most outstanding example in the 1914-1918 period. Three classes dominated British airship efforts, the SS, SSZ and Coastal classes, with reported numbers of 59, 77 and 35 respectively. These seemingly large numbers, however, conceal different model numbers - no doubt related to wartime material shortages - so these batch sizes were not as large as they seem. Since they were all built before the age of mass production, their costings do not seem very relevant. Batch sizes of the same order occurred in the second World War but a number of factors render any study of their costings nugatory, e.g. they were built by a single contractor with no competition; major bought in-cost items, such as propulsion power plants, were supplied in huge production runs, etc.

Turning back to peacetime, modern era airships, only the output of Airships Industries (UK) Ltd., represents a batch of any significance. Spyrou, 1992, states that the total built by the company was 14, although components for more were laid down. The 14, however, were divided into two models: five SKS 500 and nine SKS 600. Some of the 500 class were modified to incorporate SKS 600 features and became designated SKS 500HL, a major modification requiring separate certification.

Design activity was continuous in the decade of the company's existence; it was extremely diverse coping with (apart from the basic design and certification work of the three types) equipment fits for no less than eight demonstration tasks and four major airship design programmes; not to mention the effort to appear at all the SBAC and Paris air shows. With the company now defunct, it is impossible to disentangle and allot all the costs; only the revenue figure, quoted by Spyrou, 1992, of US $55million between 1984 and 1990 has reasonable validity. That revenue did not prevent the company's passing into receivership.

To find a case more amenable to analysis the last Airship Industries design, the Sentinel 1000, might be examined. At the time of the company's receivership, design of this airship had progressed to the point where the envelope, tail unit, flight controls and gondola main structure were complete and the envelope inflated. Systems work, including propulsion and control activation systems were largely outstanding. The programme was taken over by Westinghouse on the demise of Airship Industries, with the core design team also transferring to Westinghouse management.

Work continued, leading to a first flight in 1991. The change of management, however, had also led to a change in the basis of certification from the UK to that of the US authority. This change introduced some delay, certification under the US code being achieved in 1993. While costs of this programme were unencumbered by the diversity problems of the earlier AI products, commercial considerations have naturally precluded publishing of detail, nevertheless there is some reason to believe costs from start of design through to certification were in the order of £15 to £20 million. It is understood that no further production models have been laid down, so presumably no unit price has been established. We do, however, have one unit price: that given by Spyrou, 1992, of US $5million, as for SKS 600.

The date of this sale is not stated but from the date of first flight plus certification time this was probably around 1988. This probably equates to US $6 million in 1994 dollars, making a crude guess at the balance between inflation and learning curve. Since the receivership in 1990 of course, there remains no validity in any of the prices for which SKS ships have been traded. Thus single data point represents the only valid estimate for a small category B airship sold off a small batch production line. Since the history of Airship Industries became so complex after their win, with Westinghouse, of the US Navy large airship, it is now not possible to estimate what the 'break-even' point might have been; some non-attributable opinions, however, suggested that this point would have occurred between the 10th and 15th unit (for SKS 600).

Turning now to operation costs, we find the same dearth of realistic data. It is useful to state first some of the reasons why data are so difficult to find. First and foremost is the fact that there just are not many airships. Spyrou, 1992, numbers the world-wide airship fleet actually operating in 1992, as not very different from the figure today. Secondly and naturally, operators have to be content with what the market will bear and are extremely shy about revealing their costs. Since world operations are very much concerned with advertising business, and advertising budgets are notoriously variable, little can be deduced from that source. Finally, it is evident that airships' operating costs vary on a case-by case basis and so the construction of costs bottom-up has no general validity.

Examining, then, the components of airship operating costs, it is convenient to separate these into two classes: not the usual direct/indirect but common and peculiar costs, the word peculiar in the sense of peculiar to airships.

Common Costs

Defined as common to all aircraft are those items most readily calculated. Examples are:

- Fuel, oil, helium and usual consumables. Note that helium consumption is calendar based.

- Maintenance. Most of the routine maintenance equates to that for a small aeroplane. Unusual is the need for routine helium purification, although this can be predicted and most often planned to occur at a maintenance base.

- Parts and materials. All, as normal, based on calendar or flying hours with the exception of the envelope, which will be dealt with below under the 'peculiar' heading.

- Insurance, depreciation, cost of money and general administrative overheads. These costs are generally as predictable as for any business.

Airship Peculiar Costs

These costs can be treated under four sub-headings: Ground Handling, Mobility, Site/Hangarage and Envelope.

Ground Handling

Unlike conventional aircraft, which can taxi unaided and be chocked and lashed and left parked unattended, an airship needs considerable investment in either personnel or ground handling vehicles. If manual handling is used an airship of GZ22 or SKS600 size can require up to 12 men to assist the airship. These men must be available at all times, at any site the airship is planning to use. If mechanical handling is used, at least two specially equipped line handling vehicles must be used. These, of course, must be - like the manpower - available at each and every site. There is currently much effort being devoted to eliminating this dominant cost item, directed at robotic systems, bow and/or stern thrusters. These devices show promise of solutions.

Mobility

Conventional aircraft normally operate from a fixed base or hub, and services at other sites are provided by resident personnel, either own company or contracted-in. Most operations are A-B-A in nature. Long haul aircraft are the only ones generating personnel stop-over costs. The airship, on the other hand, finds much of its employment in 'roving commission' type tasks. In this mode, all the personnel - aircrew, ground handlers, maintainers and local management - must rove with the ship. As Spyrou, 1992, states, costs of US$300,000 per annum can easily be incurred for hotel accommodation! Remember too, that the airship must be followed by a 'ground train' of a road mobile mooring mast and several other vehicles, each generating their own standard costs of fuel, oil, tyres, maintenance, depreciation and the like.

Site and Hangarage

For that maintenance, which requires hangarage (usually not more than once or twice per year) access to a large hangar will be required. There are still a few airship hangars in the USA and one in the UK. If tasking makes it impractical to use one of these, access to a large hangar (intercontinental wide body aircraft size) may be needed, at very high cost. Another site cost which may fall under this heading is that of pressure/weather watch. Both inflation pressure and ballast requirements may change with weather conditions. This watch is needed all the time an airship is on the ground, day and night.

Envelope

Deterioration of the envelope is really a special case of depreciation or maintenance cost. The problem applies to both the older rigid airship's outer cover (failure of which was held to be the cause of the R101 disaster) and to the modern non-rigid. In the latter case, with knowledge and diligence, the deterioration does not cause a safety problem: the deterioration is monitored by control samples attached redundantly to the hull and by discriminating inspection. The cause of the deterioration is the external environment, of which two factors are significant: ultra violet light leading to deterioration of the strength filaments of the fabric, and moisture (plus atmospheric pollutants) leading to deterioration by hydrolysis of the adhesives used in bonding the fabric structural elements. The deterioration is thus subject to unpredictable factors such as the amount and intensity of exposure to both natural and man made environments.

Currently, solutions are sought via two distinct material technologies. In the apparently more successful approach, the proprietary material 'TEDLAR' is very effective as an external protective layer, giving envelope lives upwards of twelve years. The bonding adhesives used to date with this construction scheme unfortunately in themselves present a severe and probably unacceptable environmental health hazard. The next most successful scheme uses polyurethane based adhesives and the same base for an external protective paint, heavily loaded with metallic oxide pigment. This latter scheme needs considerable maintenance; inspection and repainting leading to in-service weight growth.

While materials technology can no doubt provide an improved solution, the process of re-characterisation and qualification inevitably involves real-time exposure and is therefore slow and expensive.

Meantime, the state-of-the-art solutions imply a finite life limit. Change of the envelope is relatively easy but the cost of the envelope represents some 10-20 percent of the bare airship first cost (dependent on size) and the concomitant inspection maintenance cost is also significant. Since deterioration is not wholly predictable, the reason for dwelling upon the envelope as a special case of operating cost is evident.

CONCLUSION

The facts of history force a conclusion that lack of proper examination of the airship's proper roles and of their economics must be of some importance in understanding the lack of application of the vehicle. The airship's unqualified success in the totally appropriate role of shipping protection in two wars remains, with promotional activity, as the examples which show proof of favourable role applicability and economics. Undue false enthusiasm, to the point of euphoria, directed to unsuitable uses has also contributed to holding back the development of airships as useful and practical air vehicles while many viable applications continue to exist.

This chapter has postulated one ordered methodology aimed at establishing the true applicability of airships; it is the author's hope that, in line with the aims of this book, some such analysis is applied to any future airship endeavours.

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18

Design Synthesis

B.G. Wilson

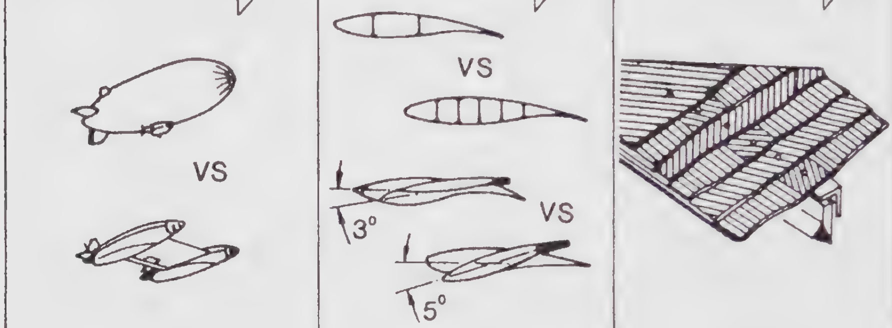
INTRODUCTION

This chapter deals with the design synthesis of the complete airship and thus covers the integration of many of the disciplines discussed in earlier chapters. The thesis of this chapter is that the process of integration is necessary for achieving a satisfactory design.

PRELIMINARY COMMENTS

Conceptual design receives more attention today than in the past. There are two primary reasons for this new importance: firstly, the new technologies present many more possible solutions in design; secondly, modern computers allow an early study of many more design variations. Parametric studies play a large part in conceptual design, establishing the sensitivity of design options at relatively low cost. Conceptual design, as a precursor to preliminary design, includes the initial creation of a new vehicle or system, the trade-off studies required to evaluate its worth, and the investment required to pursue it. Trade studies are required to provide the concept's viability for design and management decisions. If the conceptual design effort results in a viable solution, then management may decide to proceed with the project.

The engineering design effort that is required to produce a new system is usually broken down into three phases: conceptual design, preliminary design, and detail design. Conceptual design creates the initial configuration to meet a given set of requirements. Many concepts may be studied, but usually the conceptual phase focuses on a baseline design from which many trades and sensitivity studies are made. The selected design concept (or set of design candidates) will then be employed in the preliminary design phase, where more detail is added to the definition. Here, critical assemblies and the vehicle will be designed in detail, so that early weight estimates can be adjusted. Laboratory tests assist in refining the design characteristics and aid in determining the detail loads. Detail design is completed when every part has been designed, fabricated, tested, and assembled into the vehicle. The three phases are shown graphically in Figure 18.1.



	Phase I Conceptual Design	Phase II Preliminary Design	Phase III Detail Design
Known	• Basic mission reqmts • Range • Altitude • Speed • Basic material properties σ/ρ E/ρ $/LB	• Aerostatic reqmts • Fatigue reqmts • Flutter reqmts • Overall str, requirements	• Local strength requirements • producibility • functional requirements
Results	• Geometry (Airfoil shape; Ballonet configuration, l/d) • Design Objectives (Drag level, Weight; Cost)	• Basic internal arrgmt • Complete external configuration - Camber, twist distributions • Major loads, stresses, deflections	• Detail design - Mechanisms - Joints, fittings & attachments • Design refinements as results of test operation

Figure 18.1. The three phases of airship design.

The conceptual design phase is a very small part of the total (less than five percent); preliminary design represents about 15 percent of the total engineering effort; with detail design accounting for the remainder. Figure 18.2 illustrates a typical program manpower loading, and hence relates to engineering costs, for a company-funded prototype. This example is for a one-vehicle program. The powerful element of early design is shown here, where five percent of the effort commits 95 percent of the future funding. But the same five percent may save 95 percent if the project is considered unworthy of prototyping after conceptual design. In fact, less than 10 percent of all conceptual design projects are finally committed to production.

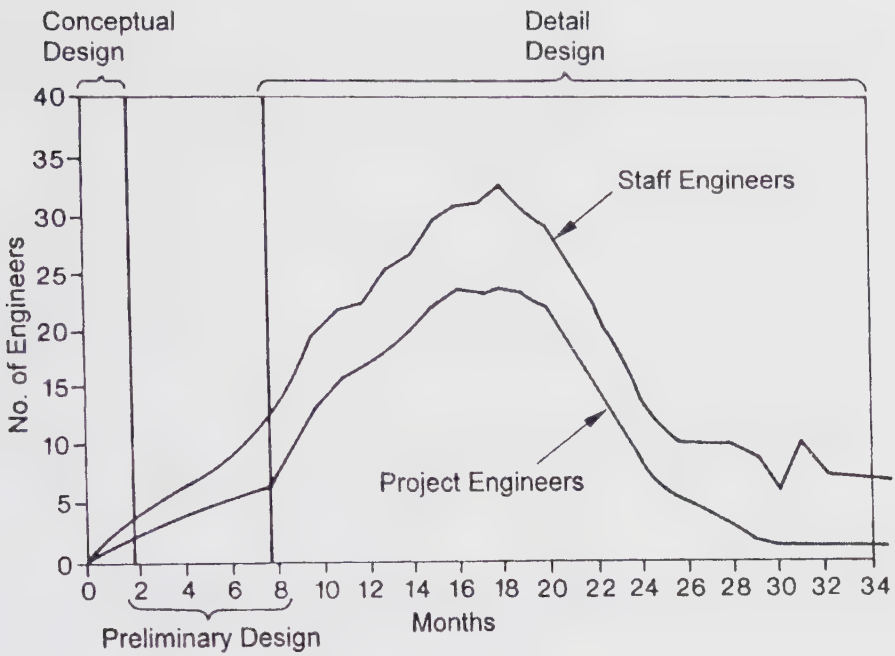


Figure 18.2. Prototype engineering manpower.

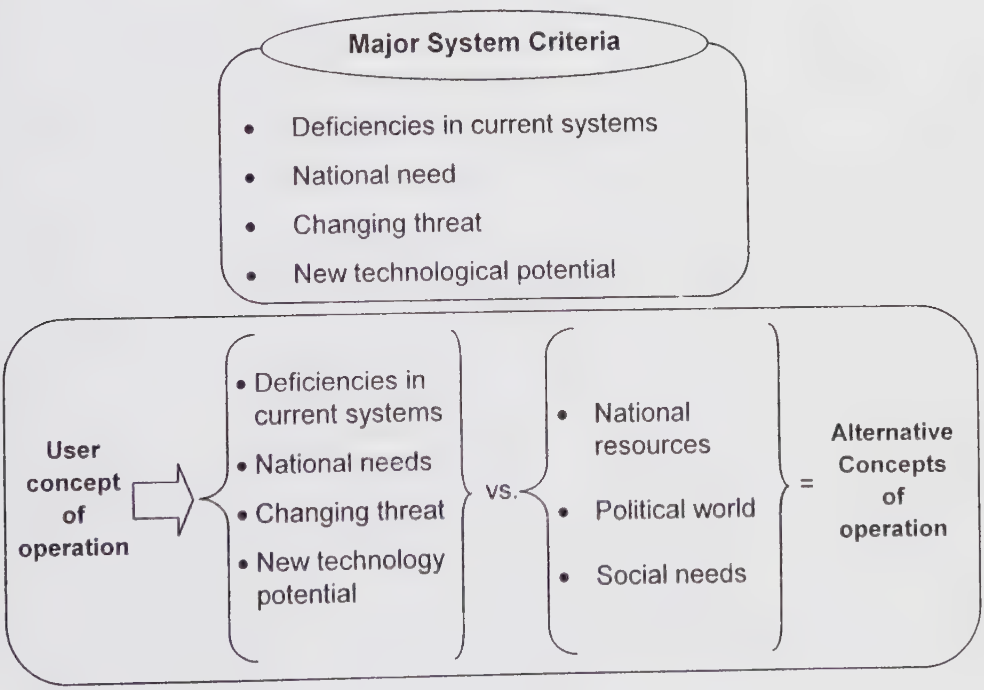


Figure 18.3. Review of basic criteria.

All design efforts are preceded by studies to identify basic requirements. Operations analyses provide the foundation of inputs to the vehicle designer. Before beginning design, a review of basic criteria should be performed. These criteria (at the top of the chart, Figure 18.3) help to answer basic questions that justify continued design efforts:

- ***Deficiencies in current operational designs*** - does the new concept offer potentially lower cost and correct other operational deficiencies?

- ***A national need*** - this is often a projection of changing world situations - political, economic, and ecological.

- ***The changing threat*** - this is a technical form of predicting national needs for survival. Threats may be defined by performance, adversary objectives, or, more subtly, by the threats of civilisation to use up natural resources and energy.

- ***New technology potential*** - technology must offer advances without degrading the system. In the case of airship application there is much technology that has been developed through other aerospace programs that is usable.

With the establishment of a set of requirements, derived from these criteria, it is possible to begin the conceptual design process.

When the decision is made to proceed with a new concept study, the process will build a data base as summarised here. The requirements will drive parameters that can be optimised with little other information. High-leverage examples are payload to be lifted, envelope volume, propulsive power required, and electrical power to be generated. The typical process for conceptual design, see Figure 18.4, is computer-aided and employs interactive modelling to cycle through initial synthesis, vehicle sizing, and computer-drawn general arrangement. It is then resized with more detailed models for geometry, propulsion, mission profile, and cost elements. Special models allow early assessment of survivability, including both susceptibility (signature assessment) and vulnerability, and design reiteration before selecting baseline characteristics.

The first step will employ a thumb-print plot that examines all possible solutions and that considers the limits imposed by known constraints, such as engine availability. A baseline design can be laid-out to verify the thumb-print and to provide a level of detail from which further trades can be extracted. A baseline trade-study process is shown in Figure 18.5. The carpet plot approach is used to look at one area of the thumb-print, with a focus on more detail and additional parameters. Sensitivities of basic parameters then follow to show the high-leverage functions and to indicate where more emphasis and technology development effort should be applied. With a growing data bank, operational trades can be investigated to measure off-design performance.

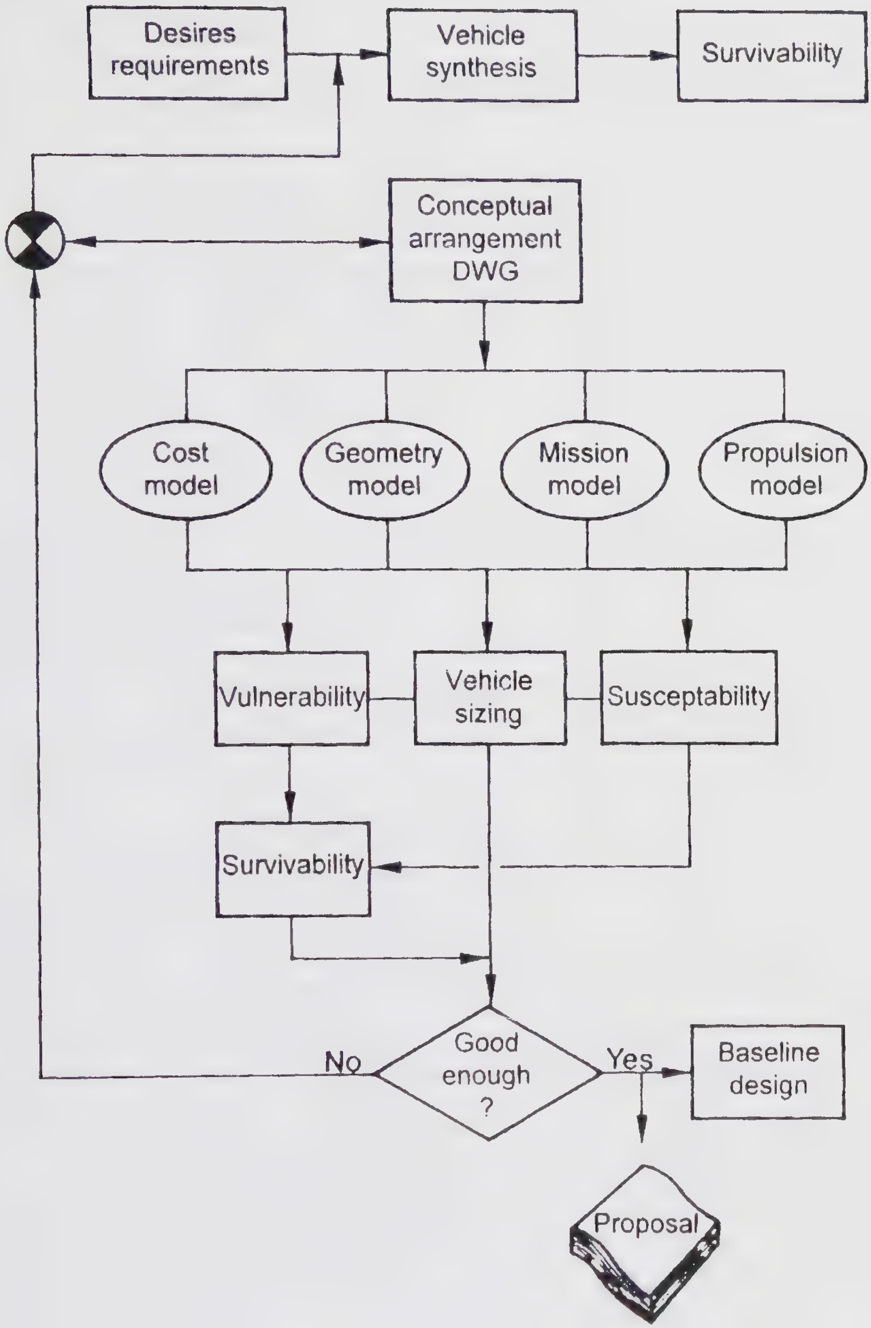


Figure 18.4. Conceptual Design Process.

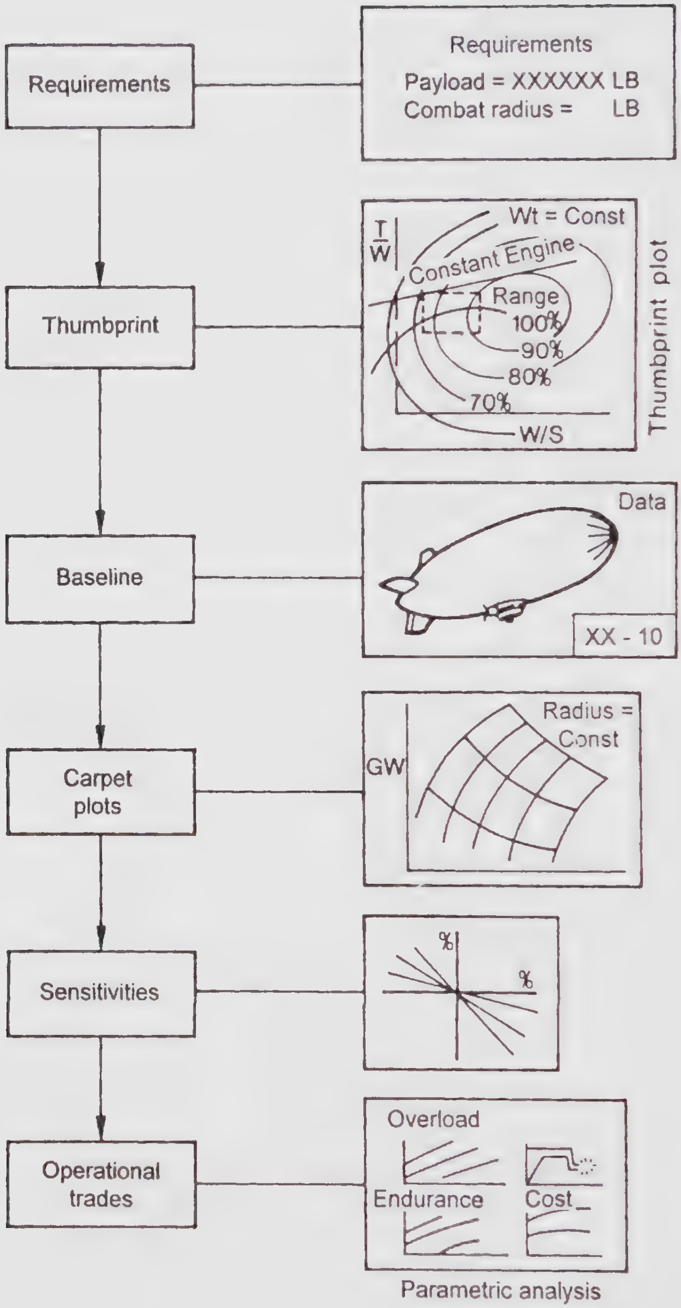


Figure 18.5. Typical trade study process.

Conceptual methods employ the baseline design as a point of departure from which to judge the value of derivatives or competing concepts. The baseline method shown here, in Figure 18.6, is generally followed for concept definition. The techniques for evaluation and subsystem trades may vary between design schools or approaches, but produce similar results. This baseline process may continue through several design iterations, each adding depth of detail and, wherever possible, benefiting from experimental data.

Traditionally, the first experiments collect aerodynamic data. Today, computational fluid dynamics produce good estimates of the linear variation in aerodynamic characteristics, and low-cost laboratories are often used to determine the non-linear characteristics. Water tunnels, small low-speed wind tunnels, and instrumented radio-controlled models offer early understanding of unusual configurations.

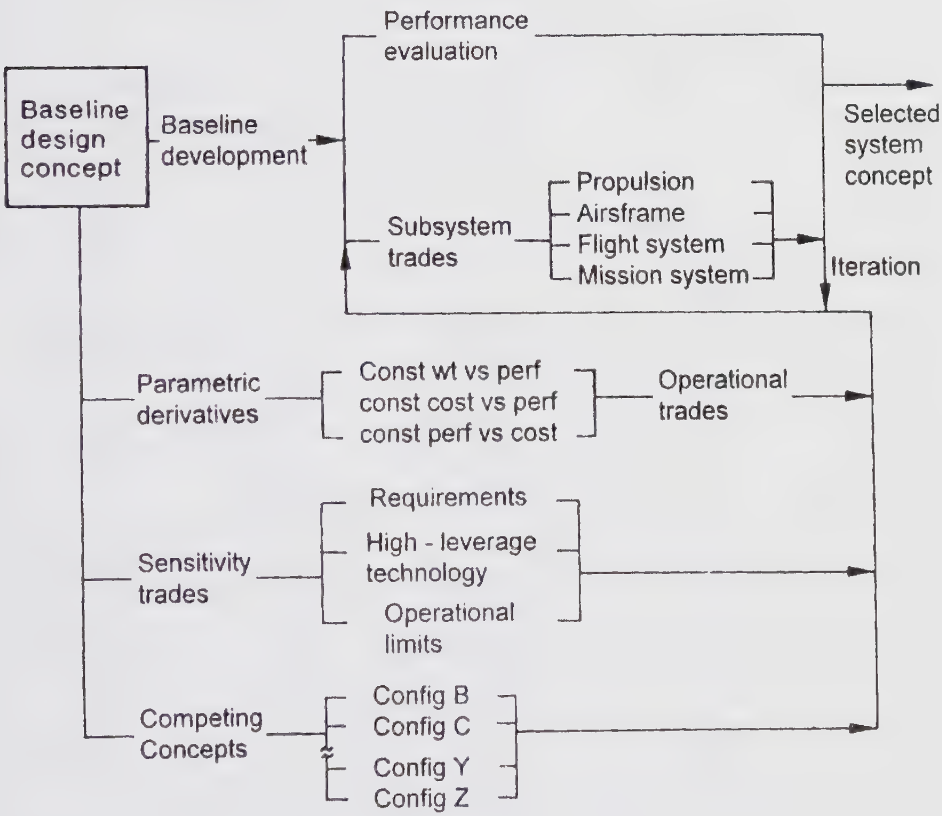


Figure 18.6. Baseline method for trade studies.

BASELINE DESIGN LAYOUT

In a conceptual design project, determination of the baseline design layout is realised by a team of specialists from a number of disciplines. The basic composition of this project team is drawn from five major design areas, as listed in Figure 18.7. The columns headed Vehicle Configuration, Airframe, Propulsion, Flight Systems, and Mission Systems each include a list of design features that fall within the respective category.

The vehicle configurator is responsible for the initial geometrical layout, and as such was often considered to be the 'designer' of the vehicle. With the increasing complexity of flight vehicles this role is now more widely understood to be that of 'initial vehicle integrator'. Airship characteristics such as volume, length, and shape definition are all determined here. Initial characteristics are estimated in brief form and then the total lift requirement is established. The resulting requirement is then used to determine the initial volume required to fulfil the mission need.

Vehicle Configuration	Airframe	Propulsion	Flight Systems	Mission Systems
• Aero Geometry • Subsystem integration • Vehicle integration • Mockups/ models • Flight simulation • Cost engineering	• Envelope structure • Body & cockpit structure • Empennage structure • Landing gear • Fittings & mechanism • Test Assemblies • Manufacture	• Intake subsystems • Powerplant installation • Secondary power supply • Exhaust subsystem • Fuel system • Emergency power • Test Instl.	• Flight controls • Mechanisms • Power distribution • Cockpit controllers • Utility controls • System simulation • Life support	• Attack subsystems • Integrated avionics • Stores managem't • Armament subsystems • Environment al control • Logistic support

Figure 18.7. Conceptual design project.

The initial derivation of characteristics is concerned with the mission payload and the space required to accommodate the crew and equipment. This activity enables the gondola to be sized, which has a first order effect upon selection of the envelope configuration, in that there is a relationship between gondola size and total envelope size. This relationship varies as a function of the type of airship being designed, i.e., non-rigid, semi-rigid, or rigid and is concerned with structural/dynamic considerations. Recording the results from these activities allows early estimation of the minimum length of the total configuration. To maintain this minimum length, a series of control stations along the body are created. The list of elements includes those that have a direct influence upon the volume distribution. The primary analytical tool here is the area plot that enables the designer to produce smooth longitudinal distributions, through the establishment of control points referred to above, while minimising excess volume created by the fairing technique. The corresponding method used in supersonic fixed-wing practice is usually the Sears-Haack distribution method. In shaping the airship, it is essential that the configuration be designed to ensure that the area distribution has a minimum of surface discontinuities that are pressure drag producers. In the case of airships, though, given the extremely large surface area the predominant contribution to drag arises from skin friction. (see Chapter 3 on *Aerodynamics* for a discussion of drag and its determination).

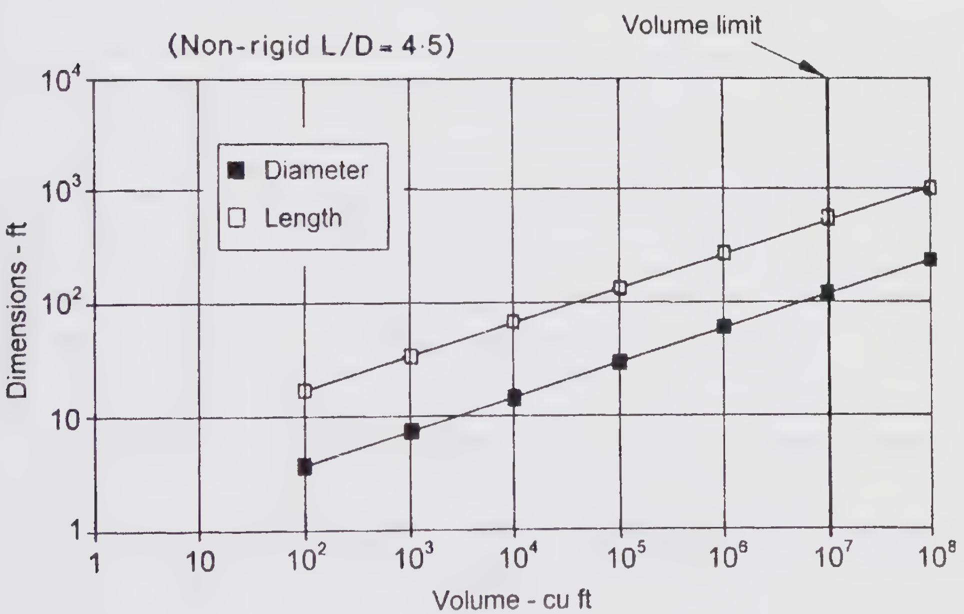


Figure 18.8. Airship geometry (non-rigid L/D = 4.5).

In configuring an airship, the conventional cross-sectional shape is that of a body-of-revolution (i.e., circular). Sectional shapes other than this have been proposed. They have included deltoid (delta planform) and ellipsoid (elliptical cross-section) shapes, but to date the preferred layout is circular (see Chapter 2 on *Basic Principles*). One major reason for this is that bodies-of-revolution possess the minimum peripheral surface for a given cross-sectional area. This then transposes into a maximum volume for a given wetted area.

An example of these relationships is illustrated in the Figures 18.8 and 18.9. In the first Figure, length and diameter are plotted against volume for the conventional shape shown. The corresponding plot of the wetted (surface) area is shown in the second Figure. The plots are called log/log in that both scales are logarithmic. The logarithmic scales are used so as to encompass as large a range of values as possible for a given plot size. As can be seen from the values on the scale the numbers are of large magnitude, with the volume values ranging from ten thousand (10 000) cubic feet to one hundred million (100 000 000) cubic feet.

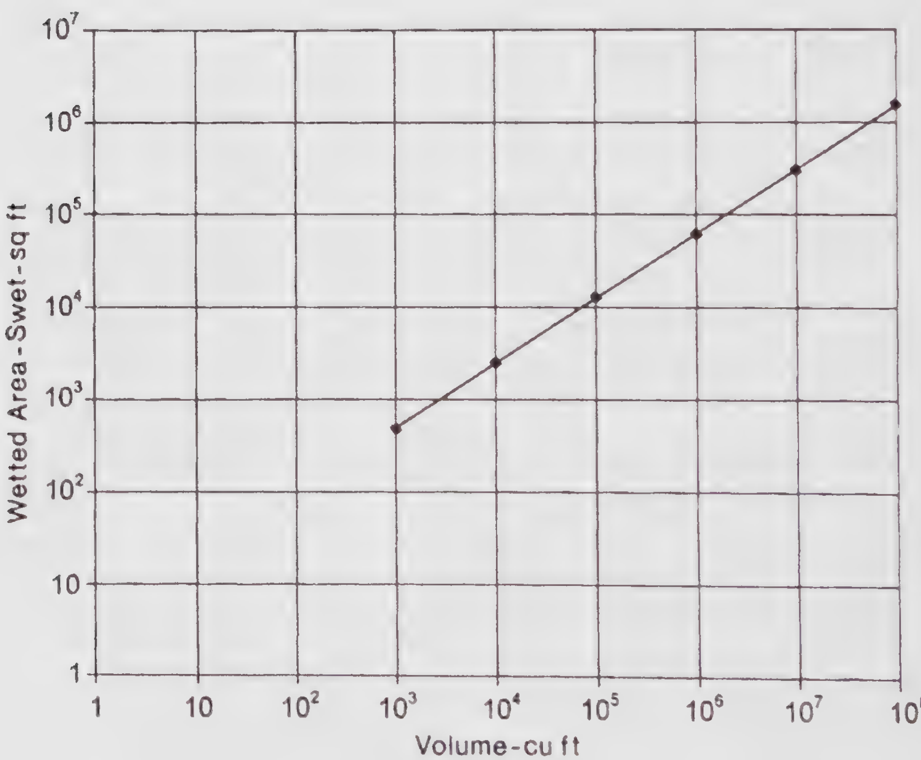


Figure 18.9. Airship volume.

One of the important considerations in determining airship size, especially for the non-rigid type, is the envelope fabric. The use of materials from the Aramid family (Kevlar in particular) reduced the weight of the envelope by a factor approaching three. A limitation exists though due to the need to internally pressurise the envelope (see Chapter 7 for a discussion on *Structures*). The level of pressurisation will then determine the speed at which the airship can travel. The practical limit for speed, in the non-rigid case, appears to be on the order of 100 knots and is governed by the maximum strength of the fabric and its corresponding seams. Thus Figures 18.8 and 18.9 both have a limitation shown at a volume of ten million (10 000 000) cubic feet which denotes the practical limit of material/seam strength. Volumes in excess of this value, and speeds above 100 knots, would necessarily be configured as rigid types. This may change as materials research progresses.

BASELINE EVALUATION

With the overall shape characteristics laid-out, the next task is to evaluate design parameters from the various disciplines. These include determination of the mass properties of the configuration, aerodynamic design, and propulsion system size. In addition to the focus on aerodynamic performance (both lift and drag), overall vehicle performance plays a pivotal role here. Cruise speed, altitude, and mission profile all drive the initial sizing.

Determination of mass properties is made using one of several methods. The methods range from a statistical approach used to estimate an approximate Takeoff Gross Weight, through the Growth Factor method (a detailed statistical approach that is more detailed by virtue of estimating component weights) to the actual weight calculation of the physical elements. The ordering of this list reflects the amount of time required for the analysis, and accuracy of the results. The first is quick and approximate, the last takes an appreciable amount of time and represents a high degree of confidence. The statistical method uses regression analysis to formulate an equation that is applicable over a broad range of sizes.

The weights discipline differs from other design disciplines in one important aspect. The analyses performed by the aerodynamics and propulsion groups use coefficients that are insensitive to vehicle size and weight. In contrast, the weights group works in absolute terms and has to determine mass, centres of gravity, and moments of inertia. Thus a comprehensive data base is essential for the accurate estimate of weight. Owing to the small numbers of modern airships that have been designed and achieved operational status, the existing database is not large. The largest amount of data applies to airships that were operational in the 1920s and 1930s. The technology level associated with airships of this vintage is lacking in comparison with that available today. (cf. Technology Trends section below).

In Chapter 9 on *Weight Estimates and Control*, concern is expressed over the statistical approach to weight determination. The reader should be aware of the several methods available, as discussed above, to calculate an initial weight of a given vehicle. The method used is usually governed by the data base of the company concerned. Most aircraft companies possess data - both for internally designed vehicles and those of the competition - which provide a comprehensive understanding of the various system elements. The use of the statistical method can be undertaken when the aircraft data base sampling is sufficiently large.

A typical example of the statistical approach using component analysis is the equation for the main landing gear of a general aviation air vehicle:

$$W_{mlg} = 0.095(N_l W_l)^{0.768}(L_m/12)^{0.409} \tag{18.1}$$

where:

W_{mlg}	=	Weight of the main landing gear in pounds.
N_l	=	Ultimate Load Factor = N_{gear} x 1.5.
W_l	=	Landing Design Gross Weight in pounds.
L_m	=	Length of the MLG in inches.

The formulation of this equation is based upon a sampling of many air vehicles. The data points are usually scattered. Therefore, regression analysis is performed to normalise the diverse values. The equations for the components can number in the hundreds for a complex vehicle, and much care is required in their application.

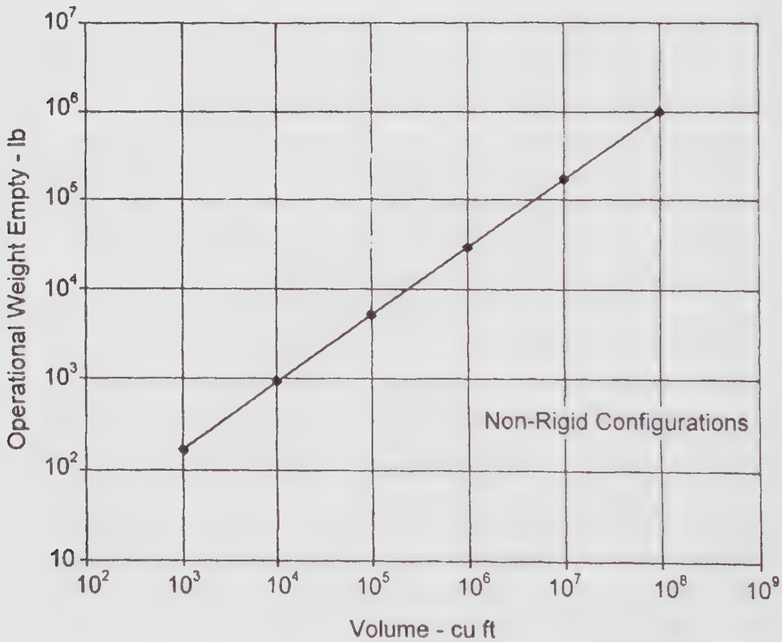


Figure 18.10. Typical weight empty trend.

The detail method estimates the weight of each component and then sums them to arrive at a total gross weight. Chapter 9 on *Weight Estimates and Control*, discusses this approach in some detail along with the relevant definitions of weight used in the airship world. A typical variation of Operational Weight Empty (OWE) with Volume is shown in Figure 18.10. The trend lines are plotted on log/log scales. The chart is applicable to non-rigid configurations only.

Aerodynamic assessment of the configuration is conducted using methods that have a much closer affinity to their fixed-wing counterparts. Some of the parameters used for reference purposes are not applicable and must be replaced. An example here in the fixed-wing case is wing area which is used as the reference for the lifting surface. Since the airship layout is very different some other reference base must be employed. A discussion of this is contained in Chapter 3 on *Aerodynamics*.

The gross lift required, and corrrespondingly the disposable lift (both theoretical maximum and actual), are determined once an initial set of weights are calculated. The various lift categories, and the definition of the terms, are described in Chapter 2 on *Basic Principles*. The estimation of the configuration's drag is conducted along the lines discussed in the chapter on *Aerodynamics*.

Within the weight calculations, account must be made for the propulsion system. As the size of the propulsion system is governed by aerodynamic/thermodynamic considerations, the thrust required (which is determined by the drag of the vehicle) plays a role in the sizing of the engines. Thus, the interplay of weight, drag, and power available are part of an iterative process that occurs from the initial design stage and continues throughout the life of a vehicle. Determination of propeller size is made during the initial design study.

The foregoing is applicable to a single-point design, but normally in the preliminary design phase it is usual to conduct a parametric analysis, as shown in the flow chart, Figure 18.5. An example of a baseline parametric analysis (in the carpet plot format) is shown in Figure 18.11. In essence, the parametric analysis consists of a number of point designs.

The carpet plot is a convenient format to illustrate the complex set of results that comprise the sizing process. The normal method is to plot various parameters against Takeoff Gross Weight or, as in the case of airships, Gross Lift. The basic sizing carpet is derived by running a fixed mission profile and varying two parameters to produce a matrix. In the example shown the two parameters are Operating Weight Empty (OWE) and Cruise Speed. Any point on the basic matrix meets the mission profile, thus the carpet plot indicates the number of combinations of the two parameters that meet the mission requirement. The minimum sized vehicle would then be at the nadir of the plot. However, a number of other parameters influence the sizing and are placed on the plot as constraint lines. Limiting values are shown for Hull Volume, Maximum Limiting Speed, and Maximum Disposable Load. These parameters, in combination, thus constrain the design solution to the lower left-hand side of the chart. Values have not been included as this chart is an example of the approach rather than a discrete design solution.

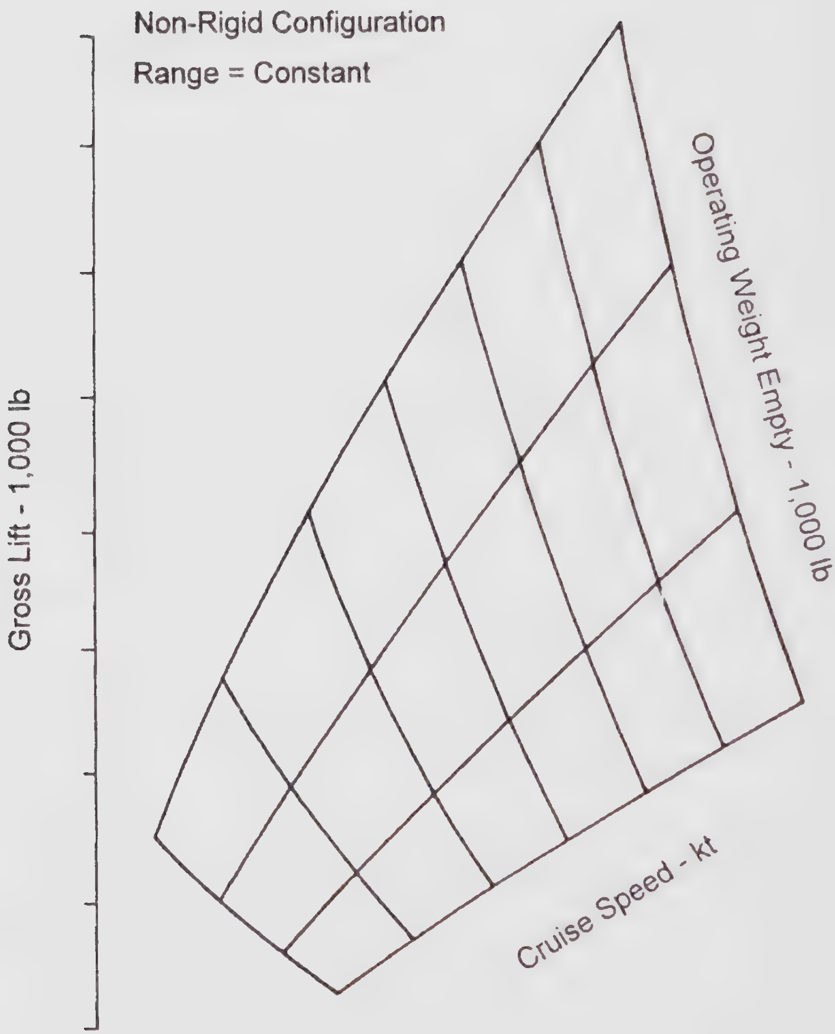


Figure 18.11. Airship basic sizing matrix.

DESIGN TRADES AND SENSITIVITIES

With the establishment of the baseline configuration from the parametric analysis, the next step is to study system components and establish their characteristics. The following discussion addresses one such trade-study that may be considered typical. What follows illustrates the level of detail that is addressed in these subsidiary studies.

For the airship in military service - e.g. a surveillance vehicle operating in the Airborne Early Warning (AEW) role - determination of the size of the primary sensor (i.e., the radar) would be paramount. A part of the sensitivity analysis would consist in trading-off its performance as a function of size, weight and power required. These three characteristics are important in that they influence the basic size of the airship. Assuming that the baseline configuration vehicle was determined by using the AEW mission as the basis for the initial sizing, the next step is to determine the threat definition that the radar is required to sense. A typical target modelling is shown in Figure 18.12 and represents a series of low radar cross-section vehicles. The plot illustrates the radar cross-section (RCS) at various frequencies for a bomber, an attack aircraft, a long range anti-ship missile, and a small medium-range anti-ship missile. As can be seen, the higher frequency X-band detects lower RCS values than the lower frequency bands for the same target. This criterion plays a role in the selection of the frequency of the radar system.

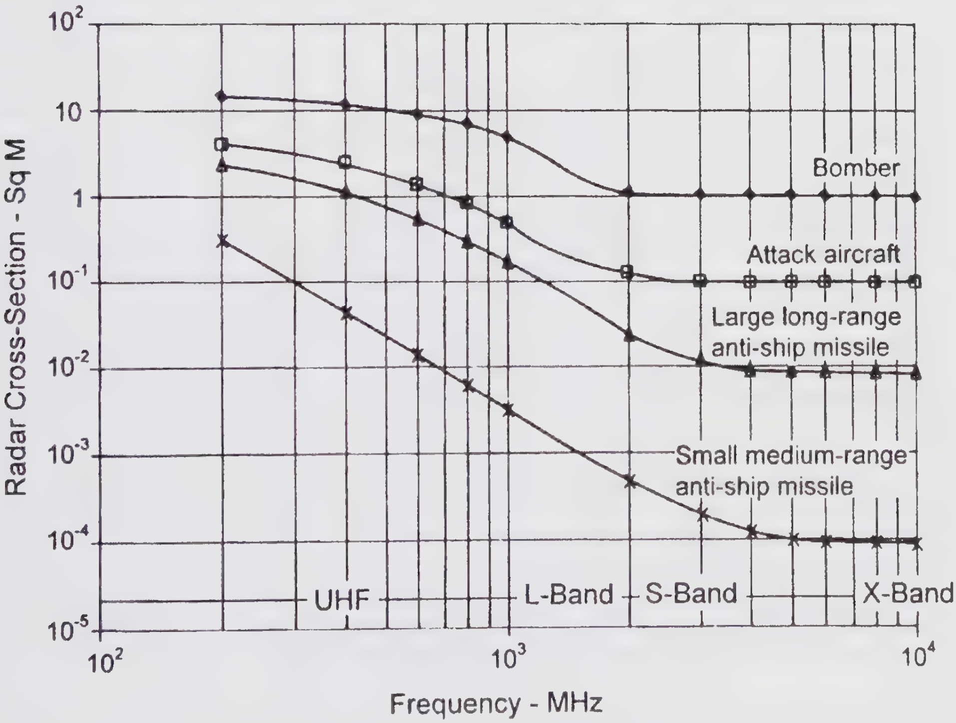


Figure 18.12. RCS modelling of targets.

A typical clutter profile model is shown in Figure 18.13 and portrays the pattern of clutter energy encountered in an airborne search system radar receiver for both !and return and sea return from near range to far range. Typical land clutter is easily one thousand times (30dB) more powerful than sea clutter, and some 40 to 50 dB higher than the target. There are a number of other models used in the selection process but space does not allow a fully detailed explanation of the method.

The choice of radar frequency for the AEW role has traditionally been driven by power/aperture considerations, coupled with the need to penetrate long ranges through all-weather conditions. When the requirement to detect low RCS targets overland is added to this, plus operation in an increasingly hostile electronic counter-measures (ECM) environment, the choice of frequency is driven toward the UHF band.

In the sizing of the radar system, consideration has to be given to prime power, weight, and cost as a function of detection range. For a given antenna aperture size, the relative complexity of the system increases with frequency. By way of example, L-band requires three times (or more) the number of components as UHF which results in higher weight and cost. One of the drivers here is the efficiency of DC to RF conversion which is significantly better, approximately 70 to 75% of UHF. Combined with lower system losses and noise figures, it is possible to design a much lighter weight system at the lower frequency.

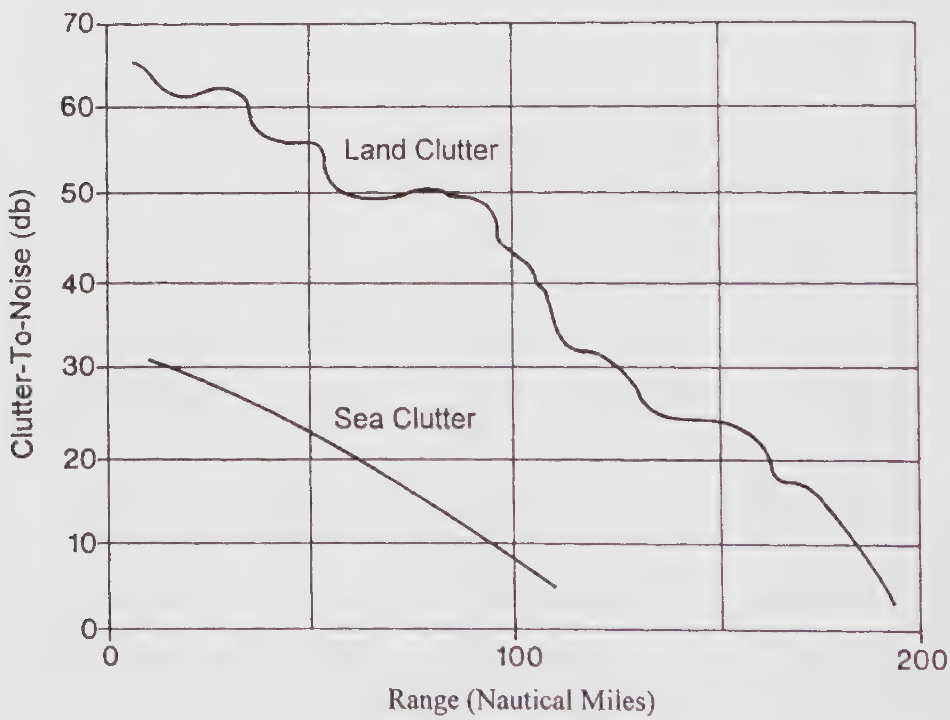


Figure 18.13. Typical clutter energy profile.

Typical trends of prime power, weight, cost, and relative complexity for three frequencies are shown in Figure 18.14.

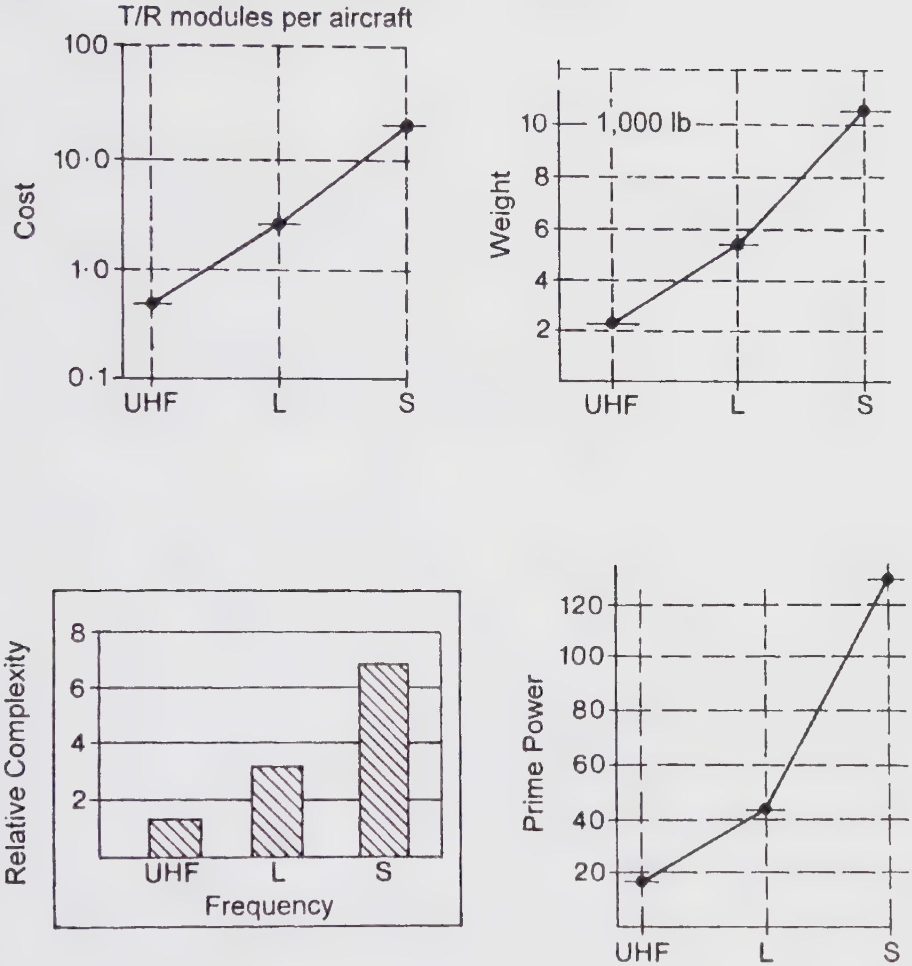


Figure 18.14. Antenna frequency selection rationale.

The actual performance trade-study used in sizing the radar is shown in Figure 18.15. The example illustrates the number of Transmit/Receive (TR) modules, by row and height for various levels of average radiated power, that are required for different detection ranges. While this example is typical for L-band, similar plots are made for other frequency bands. The conditions used for the study are noted on the chart, i.e., overland clutter profile, an array length of 6 meters and the scan volume parameters. The flat sections of the trends are noted as being the Sub-Clutter Visibility (SCV) limit of -70 dB. This figure is considered achievable given the current development of technology. The SCV limit represents the situation where clutter, rather than thermal noise, dominates the detection threshold.

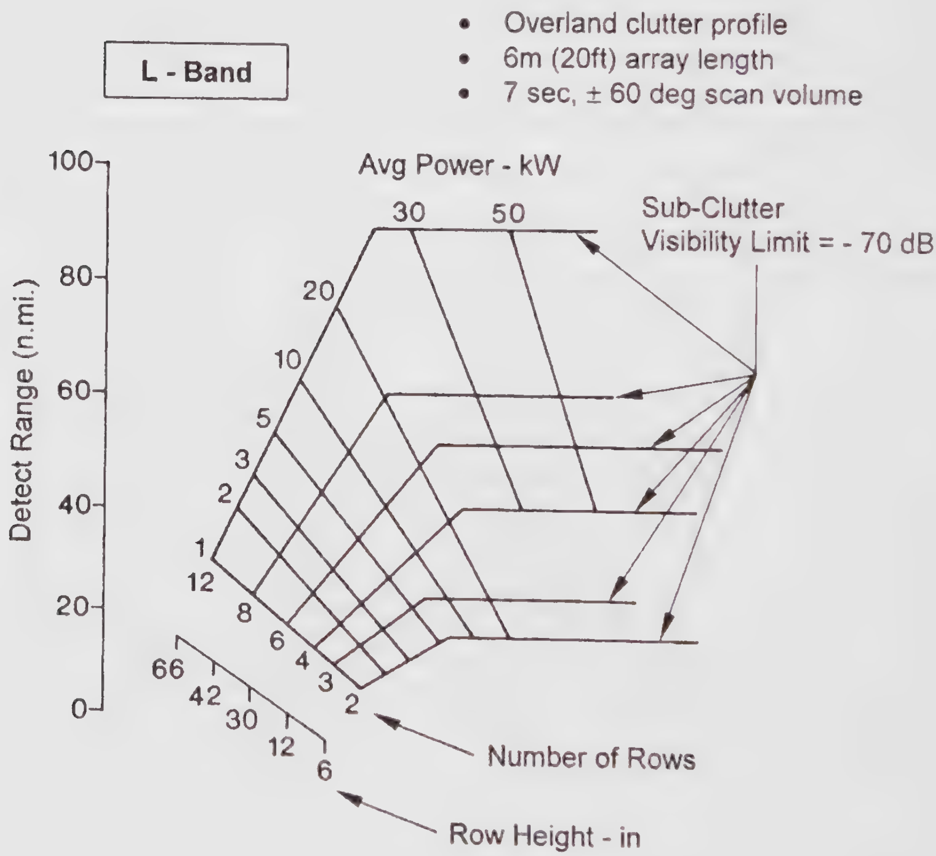


Figure 18.15. Aitrborne surveillance radar sizing.

The study is used to determine sensitivities of a number of elements, their weight, and cost - all as a function of the detection range. Typical ranges of values for both weight and cost are shown in Figures 16 and 17. Once again this is for L-band, but similar plots are usually prepared for other frequency bands during preliminary design.

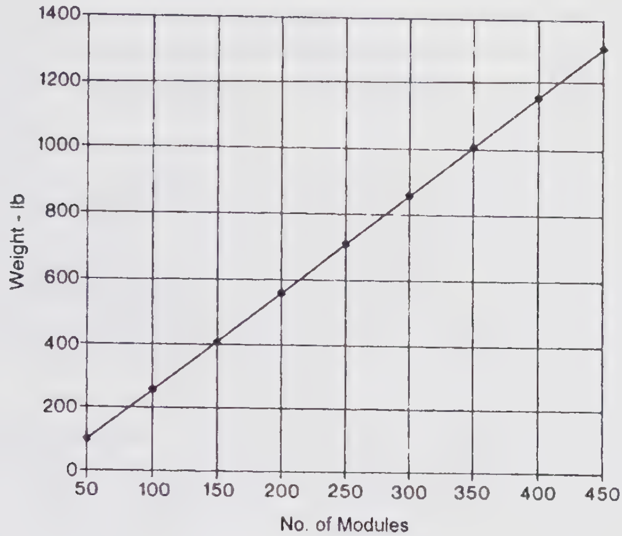


Figure 18.16. Antenna weight.

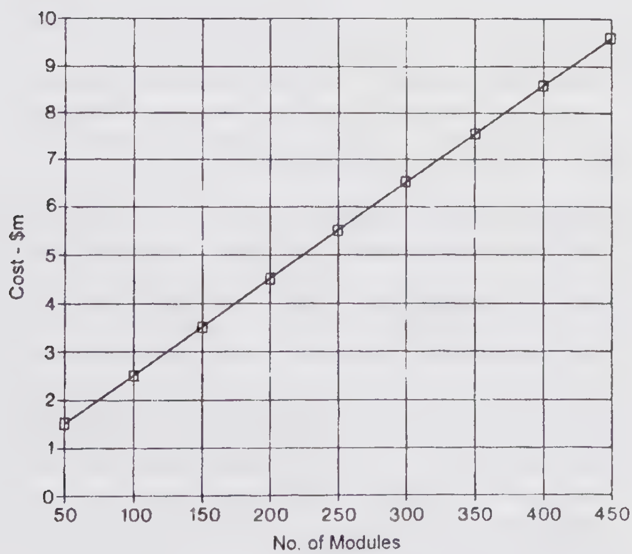


Figure 18.17. Antenna cost.

The trade studies are conducted as part of the design process and are mainly concerned with the technical aspects of the configuration. There are, however, many other trade studies performed that are not directly concerned with the design approach, but rather with the complete life cycle of the airship, the reliability and maintainability of the overall configuration, the flyaway cost, the cost of operation and support in day to day flying, and many more. The cost arena is a complex one because it is governed by whether the operation is commercial or military, the specific application that the airship would be used in, and how the particular operator would break-out the cost, i.e., the cost structure. Because there are very few airships in service, in comparison with aircraft, it has not been possible to arrive at a standard way to determine these various levels of cost. To arrive at a preliminary understanding, one possible option is to utilise the methodology advanced by the Air Transport Association of America in the jet aircraft era. This methodology only addresses the direct operating cost, but has certainly proved useful in the aircraft world. Its use, when applied to airships, must be modified since there are a number of discrete differences that must be accounted for. For example helium usage, numbers of crew, and spares holding are all different.

The parameters that are drivers in the direct operating cost (D.O.C.) calculations are utilisation, flyaway cost, crew costs, and maintenance costs. Thus direct operating cost is of extreme importance in the selling process. Competitive pressures have caused direct operating cost to play a large role early in the design of vehicles due to the influence of design on flyaway cost.

A typical carpet plot is shown in Figure 18.18, and illustrates the sensitivity of the direct operating cost to parameters of utilisation and flyaway price. The strong influence of utilisation on the D.O.C. can be seen, and represents the input of the operator. The airship price has less of a slope and thus does not have as large an impact as utilisation. The D.O.C. chart is the summary of a series of sub-calculations. The overall D.O.C. is broken out into hourly and cyclical components.

The hourly component uses block hours as the parameter, where 'block' approximates the chock-to-chock time for an aircraft. In the case of an airship, it is off-mast to on-mast time. The cyclical component represents the flight cycle, so that one flight is one cycle.

The elements that enter the calculation are grouped into: (a) airship, (b) spares and ground service equipment, (c) crew, (d) maintenance, (e) finance, (f) consumables (fuel, oil, and helium), and (g) landing and handling fees. Utilisation plays a role in several of the elements. Within (a), airship depreciation is calculated and is a function of flyaway price, salvage value, and useful vehicle life. The same calculation is made for (b) on spares and ground service equipment, with depreciation being the output. In (c) crew cost is composed of flight (pilots and attendants) and ground (crew chief, licensed engineer, and general purpose personnel). In item (d), the maintenance component is divided into scheduled and unscheduled actions, spares inventory, and consumable items. The section dealing with finance (e) accounts for the interest on any part of the purchase and the insurance of the hull. The last two sections deal with the cost of operation, viz., (f) fuel, oil, and helium costs, and the (g) landing, handling, and navigation charges. Similar cost structures have also been used by the Association of European Airlines (A.E.A.) in stating vehicle requirements.

The data shown in Figure 18.18 are integrated into the design process through the production cost targets and the maintenance functions. The results of studies made in this area are incorporated via a methodology called system engineering. The system engineering activities function as the integrator of the design disciplines and include risk analysis, risk management, and risk reduction. Assessment of the reliability and maintainability (R&M) characteristics is also made through these studies as they play a major role in determining the amount of maintenance required and hence the cost of maintenance.

The purpose of System Engineering is to ensure success in the program through a unified approach that completely defines all requirements on the system and establishes a vehicle configuration that will be capable of meeting those requirements. It is known as a 'front-end' process, because most of its tasks are performed during the initial phase of the program. The success of the program is measured in terms of cost, schedule, and technical performance. The system engineering hierarchy assists in arriving at this condition by allocating functional requirements to defined program elements. Thus system engineering involves: (a) the transformation of an operational need into a description of system performance parameters, and a preferred system configuration using an iterative process of functional analysis, optimisation, definition, and synthesis; (b) the integration of related technical parameters to assure compatibility of all physical, functional, and program interfaces; and (c) the integration of performance, producibility, reliability, maintainability, and supportability into the total engineering effort.

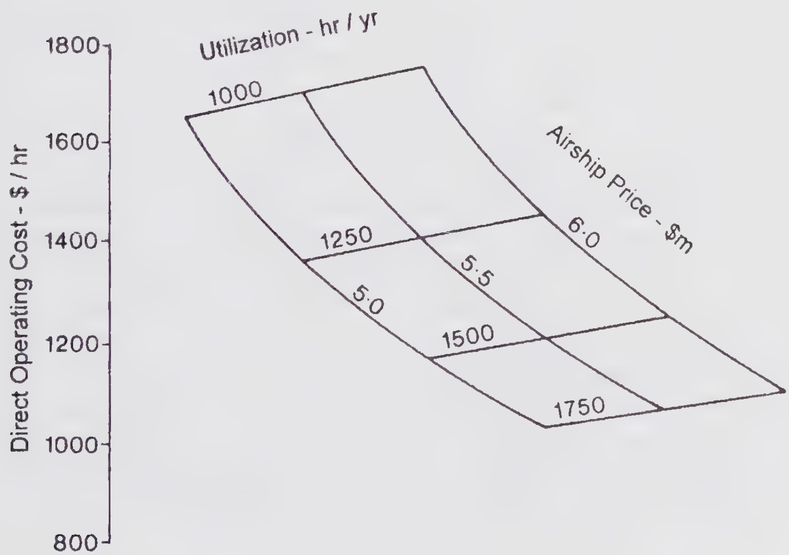


Figure 18.18. Direct operating cost.

TECHNOLOGY TRENDS

The technology level associated with airships of the vintage years is lacking in comparison with that available today. As is well-known, many of the technology developments made following World War II were not readily applied to the airship. It was not until the 1970s that any attempt was made to assess the state of technology as applied to airships, and this was done through the National Aeronautics and Space Administration (NASA) Ames Research Centre. The studies performed at that time highlighted some of the possible disciplines and areas of application. On the commercial front, the British company Airship Industries also embarked on an airship development program that utilised some of the advanced materials then available. So the trend in the 1970s was to bring the airship into the modern world through the use of available technology. The use of existing technology from other areas of application did not (and does not) address the need to perform research and development for airships in their own right. This need has continued until today, and indeed is continuing. Many of the latest designs attempt to capitalise on the new technologies - available from both the aerospace industry and allied areas - to contribute to the special needs of the airship.

The application of fly-by-light flight controls, the new materials used in envelope construction, the major attempt to address the ground handling of airships by use of the bow thruster, and the development of the new lightweight radial diesel engine all illustrate the focus that is being brought to bear in updating airship capabilities. Some of the areas that are of immediate interest have been on the periphery too long and require a major advance, e.g., ground handling. With the development of large airships, primarily for military applications, a number of these areas would necessarily have to be addressed, more especially cockpit design and a completely integrated flight control system. There is need to apply the lessons learned from V/STOL aircraft such as the Harrier in the integration of flight controls given that current airships use thrust vectoring as part of the flight control system. With the research and development being applied to the use of a bow thruster for masting/demasting the need becomes even more apparent.

As was stated above technology development as applied to airships was close to non-existent from the 1930s until the 1970s. The only work carried out being that by Goodyear. The NASA funded studies in the 1970s attempted to provide a comparative assessment as to the differences between the state-of-the-art in the 1930s and that prevailing in the 1970s. Two examples are taken from the NASA study to illustrate the approach taken.

The first example of this difference is shown in Figure 18.19 where a typical empty weight versus volume trend is plotted for a non-rigid type airship. The trend lines represent the change in technology by comparing the trend in the 1930s with that of the mid-1970s. The line in the centre is a mean of several non-rigid and rigid airships from the 1930s with cruise speeds ranging from 30 to 70 knots.

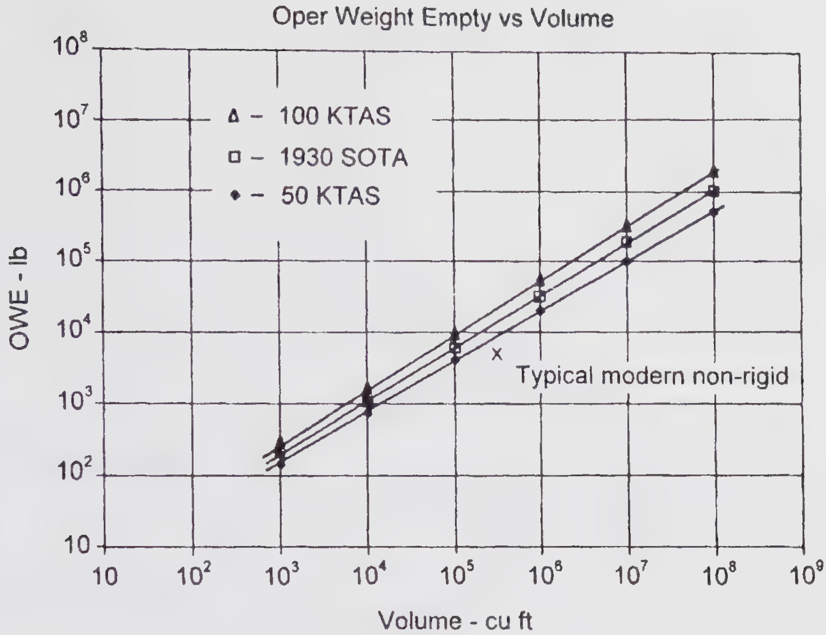


Figure 18.19. Weight trend.

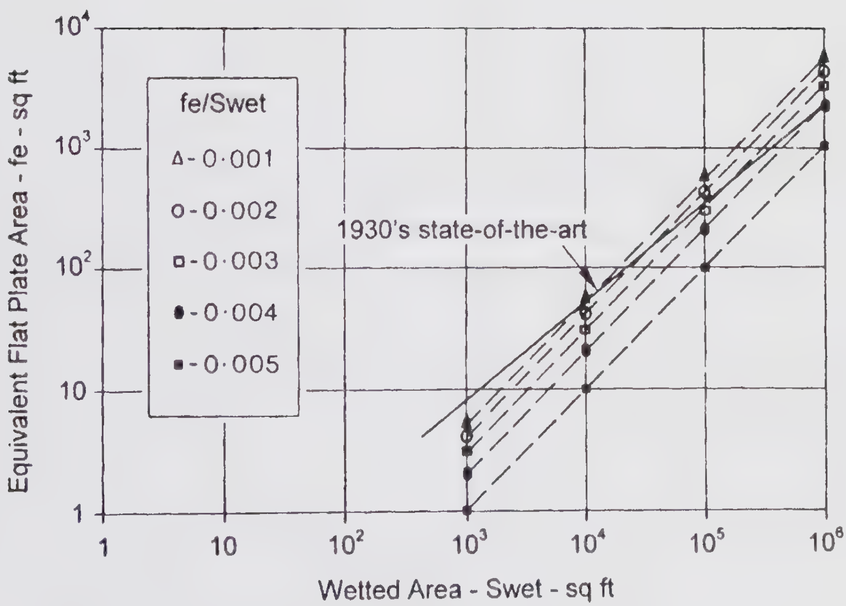


Figure 18.20. Drag trend.

The weight trend is typical for the 1970s for cruise speeds of 50 and 100 knots. In the lower 1970s case (50 knots cruise speed), it can be seen that the weight reduction due to advanced technology can be expressed either in terms of a straight-forward weight reduction (for a given volume) or a volume reduction (for a given empty weight). The weight reduction is in the order of 20 to 30 %, and is primarily attributable to the improvements made in envelope materials. The upper line (100 knots cruise speed) actually indicates a weight increase.

The increase, of approximately 30%, being due to the higher aerodynamic loading associated with the higher speed compared to the lower 1930s speed.

The other trend comparison is that of drag as shown in Figure 18.20, where the equivalent flat plate area (f_e) is plotted against wetted area (S_{wet}). The 1930s state-of-the art trend is shown as a solid line and represents a mean line as in the case for weight; this time including both non-rigid and rigid types. Given that a typical 1930s airship had a value of 182 x 10^3 cubic feet for the wetted area, the resulting $f_e : S_{wet}$ would be on the order of 0.0033. Basing the 1970s example on an improvement in envelope materials (which also assists in providing a much smoother surface and a lower drag figure), the corresponding $f_e : S_{wet}$ figure would approximate to 0.0030, thus indicating an 8% reduction for the same cruise speed of 50 knots.

These examples are just two among many that illustrate the changes that have taken place in the world of airship design. Other trends include improved permeability of the envelope and lower specific fuel consumption of the engines.

DESIGN SYNTHESIS

The design process then is an integrated function combining each of the above considerations. The nature of the interdependency of technology is illustrated in the flow diagram of Figure 18.21, which shows the process of concept development and definition to be a highly iterative one that seeks the optimum balance between the inherent priorities of each discipline. The process also recognises that candidate concepts in the several disciplines must be integrated to provide a reasonable design compromise. At the same time, the method acknowledges that constraints that may represent a reasonable objective for one concept may be unsuitable for another due to the design approach employed. For this reason, the geometry, mass properties, aerodynamics, and propulsion constraints selection as depicted in Figure 18.21, emphasise that the overall success of the design process may be measured by a figure of merit such as minimum gross takeoff weight. It is evident that the ultimate identification of reasonable performance constraints applicable to a particular concept must come in the design and analysis of the concept.

The design commences with the definition of the requirements. The vehicle is required to lift a specific payload, carry it over some distance, at a selected altitude, flying at a cruise speed, and operate at certain temperature conditions. In the first instance, it is possible that only one mission will be specified. Later, however, additional missions will be added and a number of off-design conditions studied.

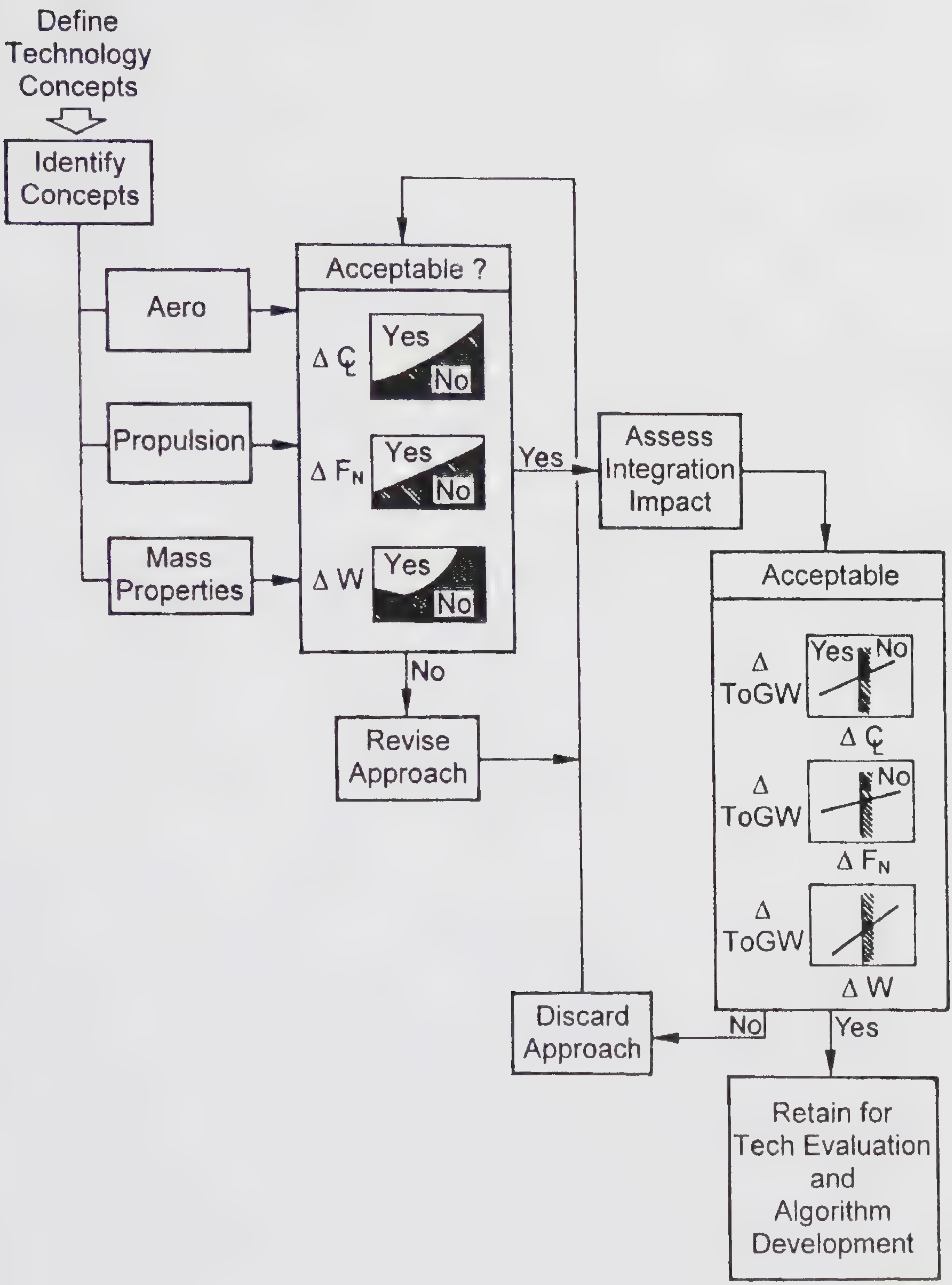


Figure 18.21. Technology Interdependence.

The next phase begins with the process of defining the airship geometry, i.e., the actual shaping of the design concept. The first estimate at a gross weight requires: (a) the hull type to be specified; (b) the dynamic lift to be estimated; and (c) the lifting gas selected. With these parameters, it is possible to arrive at an initial estimate of the hull volume. This is because the parameters provide an indication of the characteristics of the lifting gas (as the buoyant fluid) especially its specific weight, the buoyancy ratio, and the required pressure altitude. The hull geometry is defined and developed by solving the volume equation to determine the fineness ratio for a given hull type. As the hull shape is developed, attention must be given to the control curves that define smooth longitudinal fairing and transitions. The controls then become the control points in the cross-sectional views.

The design is drawn, the hull cross-sections are established, and the airship perimeter and cross-sectional area are calculated. Gondola volume is determined to verify that adequate space is available for the disposable load, i.e., payload, fuel, and ballast. The physical relationship between the gondola and envelope is checked to ascertain that the suspension system is within bounds. The design is checked for balance and the tail(s) sized. Also, a check is made into any possible physical interference between the structural elements.

Propulsion/airframe integration is an integral part of the conceptual process. The propulsor ducts have to be configured, propeller(s) sized, engine type selected, and engine location determined - all to a first approximation. Each of these elements is added to the configuration within the iterative design process. If any problems become apparent, the original scaling assumptions and geometry limitations are appropriately modified and the cycle of generating new physical data and verification is repeated.

With the configuration defined to this level of detail, the aerodynamics group estimates the lift and drag characteristics. Calculation of pitching moment and other stability and control parameters is made later in the process.

The weights are estimated for the major elements of the configuration. Group weights for the structural system (including envelope, tail surfaces, and gondola), and the propulsion system are derived. Additional assumptions come into play here, e.g., limit design load factor and gust load factor. These group weights are then combined with the weight of fixed equipment and the disposable load (payload, initial fuel estimate, and ballast) to produce a first estimate of the mission takeoff weight.

The baseline configuration is then 'flown' over the mission profile in order to determine the initial performance capability. This activity is conducted in parallel with other trade studies. Analysis of the baseline will establish the parametric field to be studied. Using the data from each of these technical disciplines, the cost of each design in the parametric set is determined as a function of structural material used, its weight, engine size and type, additional equipment used, and the design requirements, i.e., maximum speeds and loadings. The costs can be exhibited in several forms such as flyaway cost, research and development budget, and life-cycle cost (over some specified period such as 10, 15, or 20 year time-frame). Performance data are generated for a series of design points in the parametric field and these constitute the basic sizing grid or carpet plot. Evaluation of the airship is made on the basis of constant performance, constant airship weight, constant airship costs, etc., depending on which is the most demanding requirement. The carpet plot is simply a method of overlaying data to compare parametric variation. The usual approach is to plot two major parameters of interest against mission takeoff gross weight (or gross lift) to form the basic sizing plot. The resulting parametric field provides the design space upon which any number of constraints may be plotted. This is illustrated in Figure 18.22 which is a development of Figure 18.11. In this case, Operating Weight Empty and Cruise Speed are the two major parameters of interest and are plotted against Gross Lift as the payoff function. Superimposed on the carpet are the constraints of Hull Volume Limit and Maximum Disposable Load. These two limits, along with the Maximum Limiting Speed, indicate the Maximum Gross Lift achievable. This design point occurs at the intersection of the Maximum Limiting Speed and the Maximum Disposable Load curves as indicated. The carpet plot also functions as a summary plot of a number of the trade studies by presenting their results in the parametric field. Direct interpolation of study results is possible when presented in this format, which aids in the design decision.

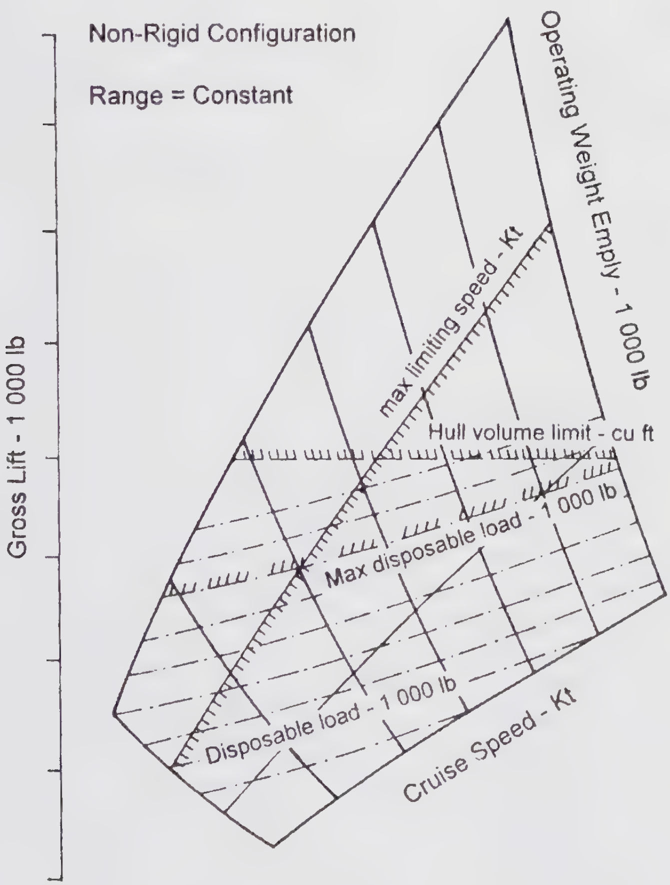


Figure 18.22. Airship sizing matrix.

A very brief overview of an airship design process has been provided in this chapter. The approach discussed is one among many but the resulting design should not be too dissimilar to those emerging from other methods. The level of complexity that the design synthesis can embody is only dependent upon the number of parameters that have to be studied. Thus, while the points referred to here appear to be simple, all that has been shown is a top-level example.

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This book provides a unique and indispensable guide to modern airship design and operation.

Airships today incorporate advanced technology including composite materials, complex electronic systems and fly-by-light controls. They demand the latest theories in aerodynamics, stability and control and require the use of advanced design tools such as numerical finite element structural analysis and computer aided design. This comprehensive and fully illustrated account brings together airship specialists from both universities and industry. After a general introduction, the essentials of aerostatics, aerodynamics, stability and control, propulsion, materials and structures are covered. The following chapters consider weight estimates and control, ground handling and mooring, systems, performance and piloting. The final chapters examine suggestions for improving airship performance, survey unconventional designs, synthesise various design elements, and look at airship roles and economic considerations vital for the success of the airship in the market place. Detailed references are also included.

This book will be of interest to airship designers and engineers, professional and student aeronautical engineers, and also to airship enthusiasts.

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