A review of airship structural research and development

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A review of airship structural research and development

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ABSTRACT

The research and development of diverse types of airships are reviewed in this paper. The early history of non-rigid, semi-rigid, and rigid airships is first introduced. It is followed by a description of a wide variety of unconventional airships with distinct features due to unique shape design, lifting gas, operation mode, or payload capability. The current ongoing airship projects in the world are summarized and the characteristics of hybrid airships and heavy-lift air vehicles are analyzed in greater detail because of the increasing interest in their development. The techniques of modeling, structural analysis, and simulation used during airship development are reviewed. Also, the optimization of airship body shape is briefly discussed. The main emphasis of this review is on the consideration of the structural aspects.

Contents

1. Introduction

Lighter-than-air vehicles, popularly known as airships or dirigibles, started with hot air balloons and evolved to lifting gas filled, tethered and un-tethered aerostats, airships, and novel buoyancy air vehicles in step with the advancement of new materials and technologies. In this paper, the word airship is used to denote all the air displacement vehicles that obtain buoyancy from the difference between the weight of the inflation gas within their hulls and the weight of the ambient atmosphere their bodies displace. This classification includes all airship-type vehicles with control and propulsion systems: traditional airships,

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unconventional airships, non-rigid, semi-rigid, and rigid airships, hybrid airships, heavy-lift air vehicles, high altitude airships, buoyancy assisted lift air vehicles, etc. Balloons and aerostats are not included in this catalogue because they do not have powered means of propulsion. Airships can be classified based on hull configuration (non-rigid, semi-rigid, and rigid), the way of producing vertical force (lighter-than-air, heavier-than-air, and hybrid), and payload capability (heavy-lift and medium-lift). The payload of traditional buoyancy air vehicles is usually less than 30 tons, while heavy-lift air vehicles can reach as high as 500 tons. Airships can also be divided into conventional types and unconventional types [1]. In unconventional airships a major feature of the airship is distinctively different from the "conventional" type. The alteration could be attributed to shape and component design, lifting gas, unconventional lift method, payload, or power source. Generally speaking, conventional airships have a streamlined axisymmetric body, generate aerostatic lift by a hull with enclosed gas, have low payload capability, and use fuel as power source. All the other types are categorized as unconventional airships.

Airships have a great range of performance capability available to be exploited. One main advantage of airships is the low cost of energy consumption. Airships can hover for a long time without refueling and their operating costs are much lower than that of conventional fixed-wing airplanes or helicopters [2]. Airships combine the advantages of both ships and airplanes. The speed of airships is higher than that of ships, their vibration levels are lower than that of airplanes, and they are not affected by sea state and a corrosive environment. Additionally, they can be boarded without the requirement for long runways. This enables them to transport heavy cargoes in remote areas. An airship transportation system causes low air and water pollution. It can meet challenging tasks for which airplanes and helicopters are not well-suited. Low noise and vibration levels as well as low vehicle accelerations provide an ideal platform for surveillance and patrol.

In this paper, the history and knowledge base of conventional non-rigid, semi-rigid, and rigid airships are first reviewed. The second section mainly covers the airship development before 1960. The next section is devoted to describe the progress achieved in the development of unconventional airships and state-of-art of airship models. Hence, the structural modeling, analysis, and shape optimization of hybrid airships and heavy-lift air vehicles are discussed in more details.

2. Conventional airships

Early airship concepts originated from balloons by incorporating propulsion and steering systems. The airships' development involved a trial and error process, resulting in a history of triumph and tragedy. The first airship was built by the French engineer Henri Giffard in 1852 [2]. This airship had a length of 143 feet and a diameter of 40 feet. It successfully completed a flight of 17 miles at a speed of 5 mph. The first rigid airship was designed and built by David Schwarz in the 1890s, a timber merchant from the Austro-Hungarian Empire [3]. The main structural components of this airship (its skeleton and outer cover) were made of aluminum. In 1897 tethered tests ended with a crash due to failure of a propeller belt. Germany took the lead in airship development before World War I. The German company *Luftschiffbau Zeppelin* was the major rigid airship manufacturer in the early twentieth century. The legendary airship pioneer Graf Ferdinand von Zeppelin developed his first airship model LZ1 in July 1900. It had a length of 420 feet, a diameter of 38.5 feet, and achieved a speed of 20 mph. The rigid airships manufactured by Zeppelin were mainly utilized for military purposes during World War I. The Zeppelin works built a number of rigid airships. The airships *Graf Zeppelin* LZ127, LZ129, and LZ130 could carry heavy loads up to 58 tons and provided luxury passenger compartments never seen before on airships. The history of airship development before 1960 is displayed in Fig. 1 [4].

France, Italy, and Britain also developed airships during World War I. Britain was active in the construction of non-rigid and rigid airships. After the war it built the two rigid airships R34 and R38 and a transatlantic roundtrip flight was successfully accomplished by R34 in 1919. These two models were wrecked 2 years later [3]. The British airship work was stopped after the crash of the airship R101 on October 4, 1930. Both France and Italy participated in building semi-rigid airships. *Roma* and *Norge* were two Italian semi-rigid models. The first practical American airship named *California Arrow* was made by Thomas Scott Baldwin in 1904. It had a length of 53 feet and was powered by a two-cylinder 5-horsepower engine. The American airship industry started in 1911 with *Goodyear and Goodrich* as the principal early manufacturers. *Goodyear* built America's first semi-rigid airship RS-1 [4]. The United States abandoned the use of hydrogen as lifting gas due to the disaster of the Italian-made semi-rigid airship *Roma* in 1922. The US Navy's first rigid airship *Shenandoah* ZR-1 was built based on the design of Zeppelin. It used helium instead of

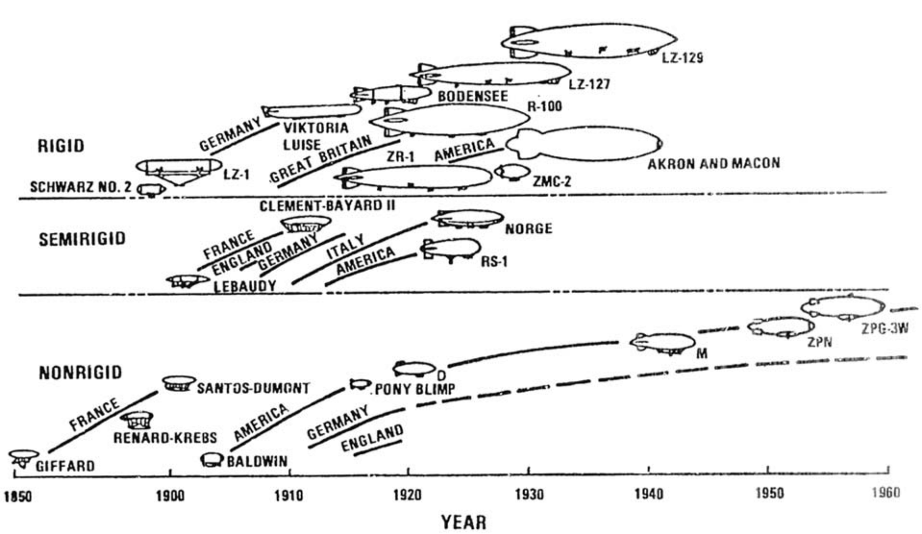

Fig. 1. History of airship development (*Source*: Ref. [4]).

hydrogen for lift generation. Its first flight took place on September 4, 1923 [5]. Italian, British, and American semi-rigid and rigid airships built between 1924 and 1935 crashed due to all kinds of reasons (fire, fog, storm, etc.) a few years after their first flights [3]. Airships were increasingly used and produced until LZ129 *Hindenburg* crashed at Lakehurst, New Jersey, on May 6, 1937. LZ129 was the largest rigid airship ever built at that time. It was over 800 feet long, 135 feet in diameter, and had a maximum speed of 81 mph.

Although airship research and development languished for a long time after the *Hindenburg* disaster, interest in airships never disappeared. After the *Hindenburg* disaster, the US Navy focused on the design and manufacture of simple, dependable, helium filled, non-rigid airships for almost three decades. After World War II the *Goodyear* company built several non-rigid airships using the latest materials and electronics. Three typical models were *Columbia II*, *Mayflower III*, and *America*. It also manufactured the largest non-rigid airship ZPG-3W in 1961. While most postwar airship projects involved non-rigid configurations, Zeppelin Luftschifftechnik initiated the development of the first postwar semi-rigid airship [5].

2.1. Non-rigid airships

Fig. 2 shows a typical configuration of classical non-rigid airships, called blimps as well. The shape of a non-rigid airship is sustained by a pressure differential between the lifting gas in the hull and the atmosphere. An envelope as the gas containment membrane encloses the lifting gas and the ballonets and provides protection from the environment. Ballonets are filled with air by blowers to maintain a fixed pressure inside as the temperature of the lifting gas or the airship altitude changes. Ballonets permit the envelope pressure to be controlled, and relative fullness of fore and aft ballonets is associated with pitch control. Adjustment of air volume in ballonets and gas volume in the envelope produces the change of buoyancy. The vertical portion of the car load is supported by an internal suspension system (adjustable catenary cable system), which is contained in the envelope and runs from the top of the envelope to the car. The principal function of the external suspension system attached to the bottom part of the envelope is to transfer the longitudinal components of the car loads into the envelope. The airship envelope fabric consists of laminated composite and is designed to withstand environment and flight loads. Lighter fabric can be used for ballonet materials because there is no flight load or environment exerted on the ballonet. The fabric used to make the envelope should have a high strength-to-weight ratio in order to reduce weight; low creep to maintain constant volume and shape; low permeability to ensure the purity of the lifting gas; high resistance to environment conditions to protect the airship from temperature, moisture, and ultraviolet radiation; and high fatigue and rupture strength to ensure the functionality of the envelope.

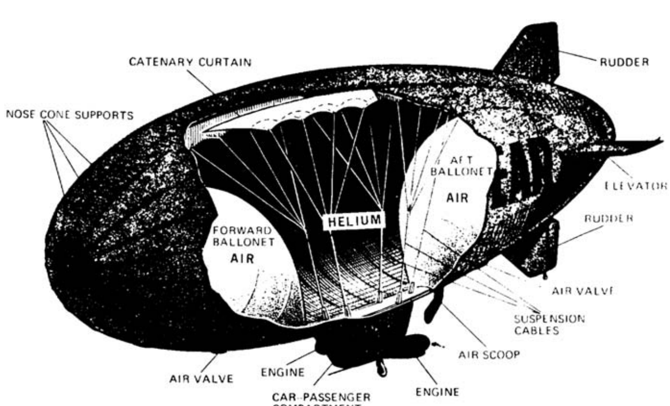

Fig. 2. Typical non-rigid airship design (*Source*: Ref. [4]).

Non-rigid airships have simple structures and are easy to design, build, and maintain. In comparison with rigid airships, the fabrication cost of non-rigid airships is lower and the manufacturing time cycle is shorter. Non-rigid airships overcome the issue of weight penalty inherent in the use of rigid structures. Non-rigid configurations are especially suitable for small airships. There are drawbacks in building large non-rigid airships [6]. A large amount of fabrics requires seaming of long length, vast working space, and special mechanical handling methods. Storage and shipping of helium for a large non-rigid airship may be a problem. Furthermore, the inflation of the envelope and the installation of empennage, nose structure, and gondola must be carefully dealt with due to the possible interaction with the pressurized hull.

2.2. Semi-rigid airships

Semi-rigid airships have some characteristics of rigid airships and non-rigid airships. A rigid keel with an aerodynamic shape runs from nose to tail along the bottom surface of the air vehicle. In contrast to non-rigid configurations, the catenary suspension system plays a much reduced role and the keel supports the primary loads. This keel is used to eliminate the main function of the caternary curtain and evenly distributes the car weight along the airship's entire length. The interaction of keel and envelope may be partially favorable and partially unfavorable. The mutual support between keel and envelope is good for resisting and distributing the bending moments between them while the poor fit of keel to envelope causes them to act against each other and generate additional stress. Thus, an accurate characterization of the interaction of envelope and keel and their mutual effects is a crucial consideration for semi-rigid airship design. It can be anticipated that semi-rigid airships have weights between those of non-rigid airships and rigid airships, since the keel on the bottom acts like a structural load bearing member.

In recent years the development of semi-rigid airships has revived. The German *CargoLifter* model CL160 was designed to have the length of the Boeing 747s (852.8 ft) and the height of a 27-story building (213.2 ft). As the key structure of this semi-rigid design, the keel provided support for loading bay, crew cabin, load frame, main propulsion units, and flight deck. Innovative aerodynamic design of the heart-shaped profile of the CL160 achieved optimal lift and high levels of fuel efficiency. A distinctive feature of the CL160 was that the loading and unloading were carried out in small areas using a patented crane-like load frame while the airship remained in the air [7]. This semi-rigid airship was capable of carrying heavy, large size goods of up to 50 m length [8], but completion of the CL160 was postponed due to lack of funds in 2002.

The Zeppelin NT-07 is a prestigious semi-rigid airship (Fig. 3) which has provided more than 65,000 passengers rides since its first operation in 1997 [9]. One Zeppelin NT-07 is used for tourism purposes in Germany. Another Zeppelin NT-07 is used since 2004 for joyrides and advertising in Japan (www.carnetdevol.org/zeppelin/world.html). A third Zeppelin NT-07 used for diamond explorations in South Africa was damaged on 22 September 2007 due to heavy winds. (www.carnetdevol.org/actualite-ballon/debeers/airship.html). The fourth Zeppelin NT-07 manufactured in 2007 was intended to perform sightseeing and special mission tasks in the United States.

2.3. Rigid airships

In contrast to non-rigid airships, a rigid airship's shape can be maintained independent of envelope pressure because the envelope is usually supported by a metal framework, as shown in Fig. 4. All external loads are carried by this lightweight structural outer shell. The external support structures are composed of a variety of transverse girders forming approximately circular frames and longitudinal girders running through the length. Transverse girders, usually made of aluminum, are connected by longitudinal girders, and are cross-braced with pretensioned metal wires for increased structural strength. Many gas cells containing lifting gas are placed between transverse frames. Gas compartmentalization of rigid airships increases safety and avoids sudden loss of substantial lift during an emergency. Lift adjustment due to altitude or temperature change can be accomplished by expansion and contraction of individual gas cells. The strength requirement of the envelope materials for rigid airships is lower than that of non-rigid airships since there are no large suspension system loads applied on the envelope. Rigid airships are usually constructed with a load-bearing frame, which allows them to accommodate all sizes and types of cargoes. Stress concentration of rigid airships is produced by the main elements of car, fins, and engines, which might be interconnected by internal structures. Recent advancements in new materials and superior connection techniques have enabled the design and construction of rigid airframe structures with high performance and light weight.

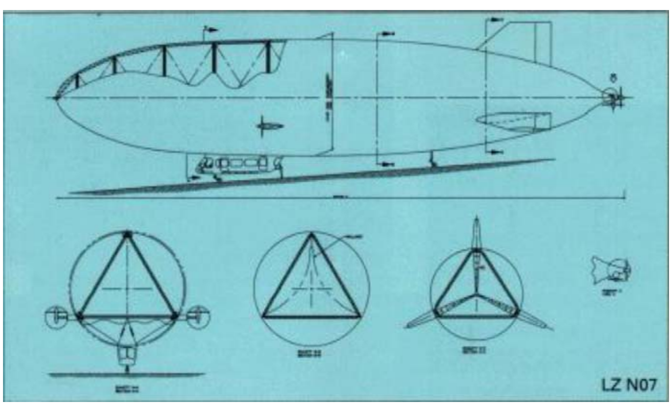

Fig. 3. Zeppelin NT-07 (*Source*: www.zeppelinflug.de).

The length of rigid airships should be large enough to justify a rigid frame. It is stated in *Airship Design* by Burgess [10] that the rigid airship is not appropriate for sizes below one million cubic feet volume. As a matter of fact, most rigid airships have volumes in excess of two million cubic feet. Though non-rigid airships are extensively employed in current practice, rigid hulls show their efficiency and benefits in large airships because there is no size restriction due to envelope fabric strength and because they have greater strength. Rigid airships overcome the possibility of nose collapse of non-rigid airships at high flight speed and allow for crew access to interior areas for inspection and repair, but the weight of rigid structures needs to be carefully considered [6,11]. Rigid airships generate increased difficulties and challenges in construction and manufacturing due to the high cost of tooling, manufacturing, and complicated assembly of structures.

As stated above, non-rigid, semi-rigid, and rigid airships have their specific advantages and disadvantages. In reality, the choice of configuration depends on vehicle size, availability of materials, tentative application, and other factors.

3. Unconventional designs

In the last half-century, there has been an unexpected and dramatic renaissance in the development of novel buoyancy air vehicles. Considerable attention has been paid to the unconventional aspects of unique shapes, hybrid operational method, innovative lifting gas, and heavy payload capability. Of particular interest are hybrid airships and heavy-lift air vehicles. Preliminary developments of some programs at the prototype stage have been accomplished, and many ongoing projects are heading towards a promising and fruitful direction.

3.1. Unconventional shape designs

3.1.1. Spherical airships

Traditionally, the preferred airship shape was the long, narrow, streamlined body of revolution, which achieves a tradeoff

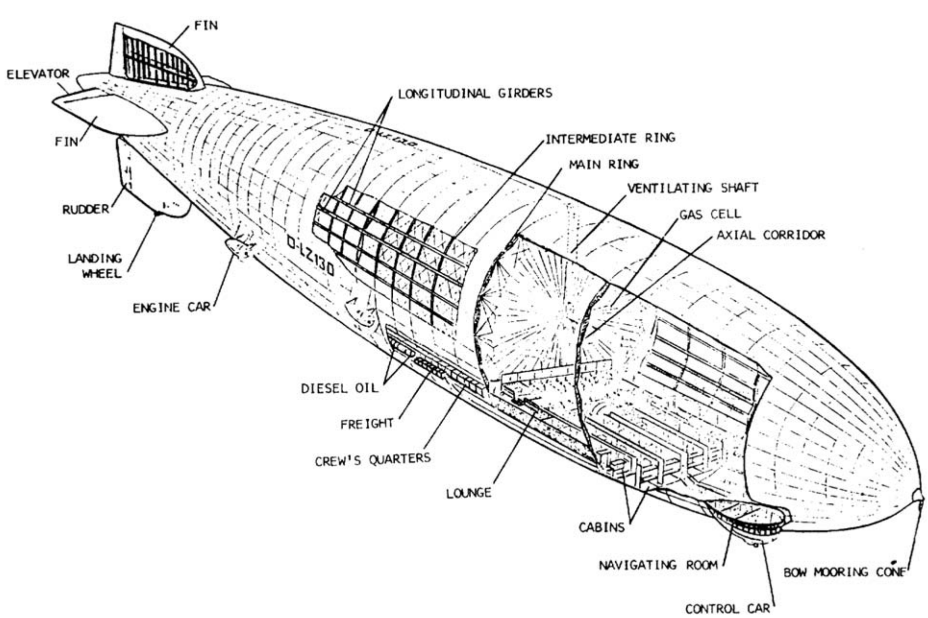

Fig. 4. Typical rigid airship (*Source*: Ref. [4]).

between maximum lift and minimum air resistance. However, adopting the shape of free-floating balloons, modern airships can be spherical. A Canadian company, *21st Century Airships Inc.* has built six prototype airships with perfect spherical shapes (www.21stcenturyairships.com). As illustrated in Fig. 5, this kind of airship is not equipped with control fins and an external gondola. Instead, the gondola is enclosed in the envelope at the bottom of the sphere and two engines are mounted at protruding wings outside the envelope. Though spherical shapes bring high aerodynamic drag compared with other configurations, they have distinctive merits. It is known that a spherical shape provides minimum surface area for a given volume among all the geometries. As the surface area is proportional to envelope weight, spherical shape generates maximum lift with minimum weight. Moreover, spherical shapes bring excellent features for operation and mooring: the airship does not need forward speed to land or take off as a conventional airship does; its spherical shape allows it to be moored by tying to the ground without using a mooring mast. Spherical shape and conical shapes can be combined to produce a distinct configuration [12]. Fig. 6 shows this geometrical design of non-rigid airships for rain forest exploration. Experimental research demonstrated that the drag coefficient can be reduced by about 50% by placing a cone behind a sphere [13].

3.1.2. Lenticular airships

The British company *Thermo Skyship* contributed to the design of lenticular airships and they flew a radio controlled lenticular airship model in 1975 [1]. Between 1975 and 1990, Mario Sanchez Roldan and Michael K. Walden built the rigid lenticular airships MLA-24, MLA-32-A, and MLA-32-B (spot.colorado.edu/~dziadeck/airship/mexico.htm). It is worth noting that MLA-32-B was the first manned fully rigid airship in operation for over 50 years. Besides Britain and Mexico, Russia also attempted the construction of the lenticular airships *Thermoplane* [1]. An intrinsic problem associated with this configuration is the high drag due to the high surface-to-volume ratio. Lenticular airships are easily affected by payloads during mooring in contrast with traditional airship bodies. The lenticular airship prototype *Alize* was produced by the French LTA corporation in 2006 (Fig. 7) (www.operation-lta.com). Lenticular airships have aerodynamic characteristics approaching those of wings and therefore make it possible to compensate for accidental overweighting (loss of helium, icing, etc.) through aerodynamic lift generation. The aerodynamic shape of lenticular airships is also helpful for flight maneuver control.

Double hull and multiple hull designs: Two or multiple conventional hulls of streamlined bodies can be joined together with or without connecting structures. This design achieves a reduction of overall length for a given volume of gas or an increase of gas compartment without an increase of overall length. Two large hulls can be connected by an inboard wing, which leads to increased aerodynamic lift and load capability [14,15]. A novel type of double-hull design of airships is displayed in Fig. 8 [16]. A double-hull configuration rather than a single hull reduces the lateral surface area and makes the airship less sensitive to lateral gusts. Double-hull designs were used for hybrid air vehicles. The

Fig. 5. Spherical airships of 21st Century Airships Inc. (*Source*: www.21stcenturyairships.com).

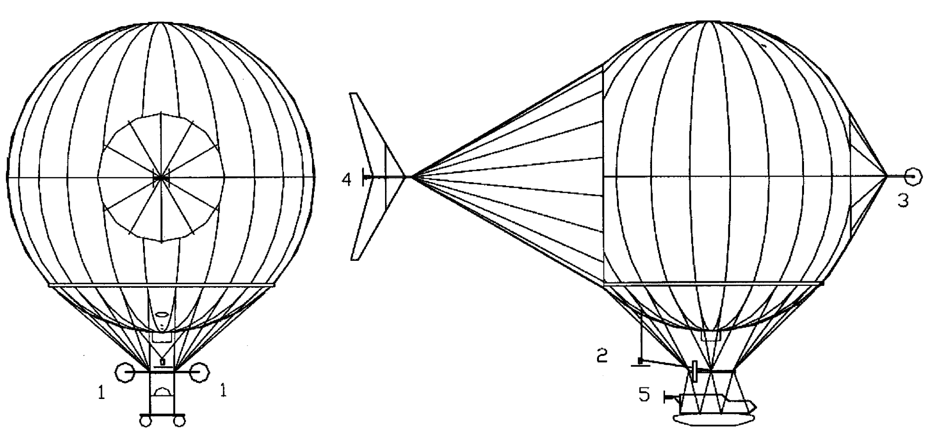

Fig. 6. Schematic of a non-rigid airship for rain forest exploration (*Source*: Ref. [12]).

Fig. 7. Lenticular airship (*Source*: www.operation-lta.com).

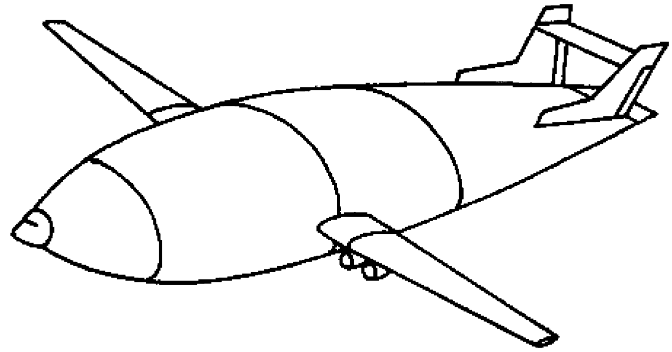

Fig. 9. Winged-airship design (*Source*: Ref. [1]).

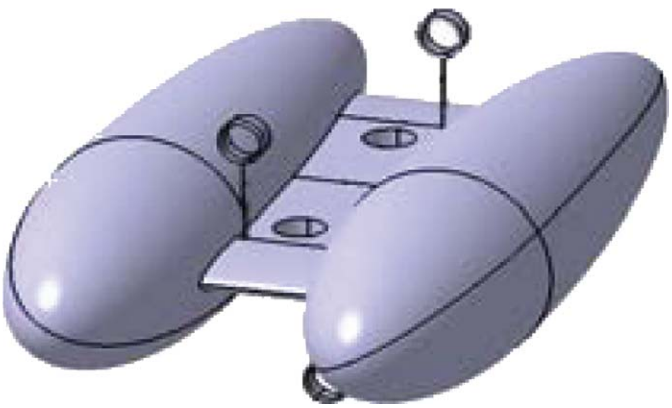

Fig. 8. Double-hull design of unmanned airships (*Source*: Ref. [16]).

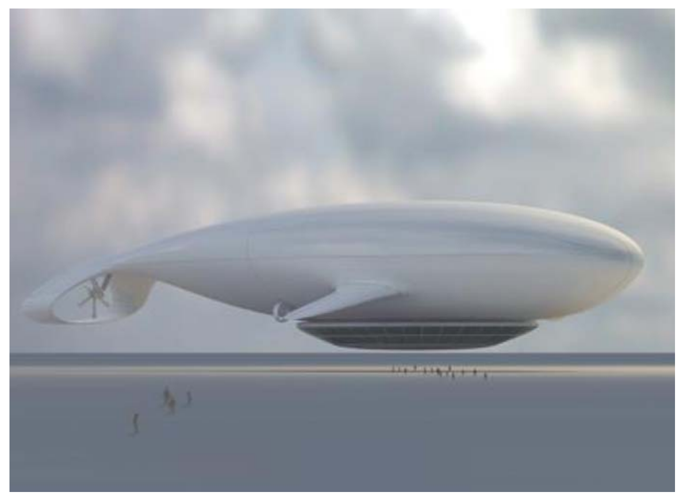

Fig. 10. Manned Cloud airship (*Source*: www.dezeen.com).

British company *Advanced Technologies Group Ltd.* (ATG) at Cardington employed a pressurized twin-hull design [17] in their *SkyCat Series* of hybrid air vehicles.

A triple-hull configuration was proposed by the *US Aereon company*, but has never been built [1]. The *Lockheed Martin's* Skunk Works designed the experimental hybrid airship P-791 in 2004 (www.military-heat.com/91/p791-hybrid-airship-project/). It was flight tested at Lockheed Martin's facility in the Palmdale Air Force Plant 42 in 2006. The P-791 has three pressurized lobes and the large span produces 20% of the total lift. No multiple-hull shapes with more than three compartments seem to have been developed. Multiple-hull designs might result in simpler construction of smaller units compared with the manufacturing of single-hull airships, although the connection of individual hulls and flight stability and control could arise as issues.

3.1.3. Winged-airship designs

The concept of winged airships stems from airplane design considerations to take advantage of the aerodynamic lift generated by high aspect ratio wings. The proposed *Ames Megalifter* in Fig. 9 has the shape of a classical airplane with the fixed wings carrying propeller turbines or tubofans. Adding a pair of high aspect ratio wings to the main vehicle body helps to produce substantial aerodynamic lift, improve vehicle stability, decrease drag, as well as increase payload capability [18]. The wings can provide natural stability under normal flight conditions. In the recent decade, the design of a winged-airship vehicle was combined with the study of reliability, safety, and stability. Feasibility analyses, numerical simulations, and prototype fabrication were carried out [19]. A literature survey shows that winged-hull airships have never been built.

3.1.4. Other unconventional shape designs

Other unconventional shapes include deltoid, dart, flat-body, toroid, and multi-balloon shapes. These hull geometries were designed to serve different purposes. The *Aereon Dynairship* with a deltoid shape was designed to generate an efficient lifting body/aerodynamic lift capacity [1]. The dart shape was chosen to achieve high propulsion efficiency [1]. The *Manned Cloud* (Fig. 10), a whale-shaped airship, was recently proposed by the French designer Marie Massaud. *Manned Cloud* functions like a flying hotel with a capacity of 40 passengers and 15 staff, and contains a restaurant, a library, a fitness suite, and a spa (www.dezeen.com/2008/01/10/manned-cloud-by-jean-marie-massaud).

3.2. Novel lifting gas: hot air and ammonia

The lifting gases of buoyancy air vehicles have a lower density than the surrounding air. The lift capacity of a variety of light gases is compared in Fig. 11. Hot air, hydrogen, and helium are commonly used. Hydrogen provides the most lift since it has the lowest density. It has been used as lifting gas in early airship design, but hydrogen gas requires extraordinary care in handling in order to avoid unwanted explosions or fires when mixed with air. Although the exact sequence of all the events in the *Hindenburg* fire and their causes could not be fully determined,

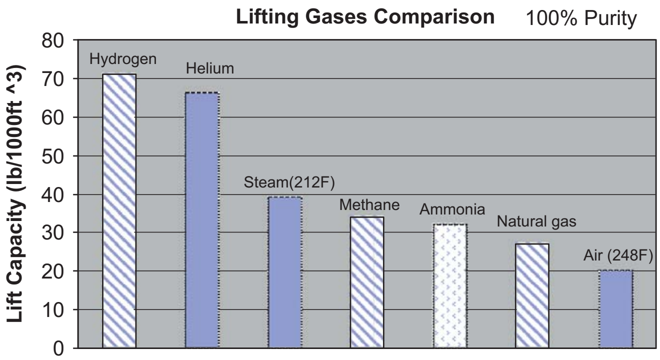

Fig. 11. Schematic of lifting gases comparison (*Source*: Ref. [4]).

Fig. 12. Hot air personal airship (*Source*: www.personalblimp.com).

hydrogen was abandoned and helium was used as lifting gas after the *Hindenburg* disaster. Helium has a 7.3% smaller lifting capacity than hydrogen, but it has the lowest density among other types of gases. Unlike hydrogen, helium is inert and incombustible. However, helium is more expensive than hydrogen and the supply is limited. Hot air at 250 F has only one-third the lift capacity of hydrogen in a 32 F atmosphere. Therefore it is mainly used in balloons. Hydrogen, methane, and natural gas are flammable, and ammonia is corrosive. Methane is relatively cheap, and the lift capability is between that of helium and hot air. It was only proposed as the primary lifting gas for the *Methane Gas Transporter* [1].

Modern airships can use hot air as the lifting gas, thus considerably decreasing the operating costs compared with helium airships. Hot air airships derive from hot air balloons. The first hot-air airship in the world was created by Don Cameron in 1972, the founder of *Cameron Balloons*—the world's largest manufacturer of traditional hot air balloons [20]. Thermal airships have blimp-like shapes, fins, and propellers. The world's biggest thermal airship was produced by the Per Lindstrand Company in 1993 for French botanists (www.airshipdubai.com/blimps.html). The *Skyacht Aircraft Inc.* developed the world's first personal blimp using hot air as the lifting gas (www.personalblimp.com). The usage of electric motors for propulsion provides a virtually silent flight environment. The Skyacht Personal Blimp (Fig. 12) has a foldable hull structure like an American football, which is made up of long, fairly flexible ribs subjected to compression and fabric and a tension line subjected to tension [21]. More information about the worldwide development of hot air airships can be found at www.hotairships.com.

A novel concept of using ammonia as a secondary lifting gas was also contemplated. By generating aerostatic lift for the payload only, ammonia provides a safe way to solve the problem of nonequilibrium aerostatic flight. Traditional methods used to handle nonequilibrium aerostatic flight include exhaust water recovery, vectored thrust, primary lifting gas venting and compression, aerodynamic lift, air liquefaction, as well as hot air or steam ballonets. Ammonia as a kind of lifting gas provides an unconventional means of addressing this issue [22].

3.3. Unconventional lift method: hybrid airships and buoyancy assisted lift air vehicles

Hybrid airships have been an active research area in airship history. The operation of traditional airships depends on the lighter-than-air condition. Hybrid airships combine the features of lighter-than-air and heavier-than-air vehicles and do not necessarily rely on conventional methods for lift generation. Hybrid airships derive the buoyancy partially from a lighter-than-air gas and partially from dynamic lift generated by shape and geometry. Hybrid air vehicles are usually found in combination with unconventional shape configurations. They may employ helicopter rotors, a wing-shaped lifting hull, a unique lifting body, or multiple hulls. Hybrid airships overcome the disadvantages of airplanes for long take-off and landing runways or of helicopters for large rotors. In the 20th century, hybrid air vehicles were classified into Dynastats (the *Dynairship*, *Megalifter*, *Dinosaure*, and *AirCruiser*), Rotastats (the *Helistat*, *Helicostat*, *Heliship*, *Helitruck*, *SLAB*, and *Toroids*), and Rotating Hulls (the *Cyclocrane*, *Aerocrane*, and *Magnus Aerolift*). A Dynastat combines the features of an airship and an airplane while a Rotastat integrates the characteristics of an airship and a helicopter. Detailed information about these hybrid airships is provided in *Airship Technology* [1]. Hybrid air vehicles can carry significantly more payloads than conventional airships of similar size and are much less sensitive to weather effects. Hybrid airships with high payload capability will be described in the subsection on heavy-lift air vehicles.

An inboard wing used to connect two hulls has an effectively infinite aspect ratio of span to chord, which precludes the loss of lift due to tip flow. The load-carrying capability of this kind of hybrid airships depends on the volume of gas for buoyant lift, and on the inboard-wing, flight speed, and altitude for dynamic lift. The combination of both lifts allows for heavy loads to be carried [14,15]. Hybrid air vehicles cannot be fully described by either airplane-derived or airship-derived relations. Boyd [23] from *SkyCat Technologies Inc.* constructed a model to evaluate the performance of *SkyCat* hybrid airships. His research work demonstrated that the efficiency of hybrid air vehicles is sensitive to size, and large vehicles are more efficient than small vehicles. Due to the requirement for large gas containment hulls, hybrid air vehicles cannot be operated at speeds greater than 140 knots. This kind of hybrid air vehicle can achieve a 60% reduction in shipping cost per ton-mile over fixed wing aircraft. At the Technical University of Munich Kuhn et al. [24] designed a demonstrator hybrid airship for ground observation which has the unique shape shown in Fig. 13. Aerostatic lift and aerodynamic lift are used for energy efficient horizontal flight, while aerostatic lift and motor thrust are used for energy-efficient hovering. The semi-rigid structure was built out of sandwich beam structures and longitudinal rods. The inner structure was attached to the hull membrane through longitudinal rods and beams.

A buoyancy assisted lift air vehicle, the *Aeroscraft*, (Fig. 14), is currently being developed by AEROS [25–27]. In distinct contrast

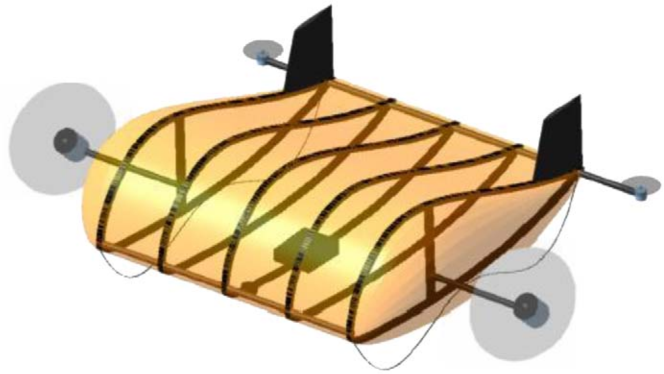

Fig. 13. Schematic of hybrid airship (*Source*: Ref. [24]).

Fig. 14. Schematic of *Aeroscraft* (*Source*: www.aerosml.com).

to hybrid airships, the *Aeroscraft* is capable of substantially and smoothly adjusting the static heaviness by changing the lifting gas pressure in the hull. With the incorporation of an innovative static lift control system, the *Aeroscraft* is designed to be a vertical takeoff and landing (VTOL) air vehicle with a heavy-lift capability. The *Aeroscraft* generates lift through a combination of aerodynamics, thrust vectoring, and gas buoyancy generation and management. The *Aeroscraft* can transport large volumes of cargo and passengers under various loading and environment conditions, and it can be used for a wide variety of applications. The *Aeroscraft* program depends on the configuration design of a rigid aerostructure. The focus of this program, funded by the US Defense Advanced Research Projects Agency, is a demonstration of the lightweight rigid aerostructure technology, which involves an analysis leading to a demonstration flight test of the aerostructure under flight load conditions. The objective is to show that the rigid aerostructure can be both light and strong enough to accommodate air loads without failure thus leading to a new class of robust buoyancy assisted lift air vehicles of high utility.

3.4. Unconventional payload: heavy-lift air vehicles

Various designs for heavy-lift buoyancy air vehicles have been proposed over the years. Heavy-lift hybrid air vehicles operating at low speeds can transport heavy loads with excellent fuel economy and therefore are considered as an efficient and cost-effective transportation tool for point-to-point delivery of massive loads. The heavy-lift airship concept was first proposed by the *Piasecki Aircraft Corp*. in the 1970s [1]. Piasecki's design was based on the integration of the traditional streamlined airship body with helicopter rotors. Besides Piasecki's quad-rotor airship design, one-rotor and twin-rotor models were designed and produced at that time. Four models of early heavy-lift airships are shown in Fig. 15 [1]. An analytical model for a quad-rotor heavy-lift airship was developed to study the performance, stability, and control characteristics of heavy-lift air vehicles. *Goodyear Aerospace* evaluated different control concepts for heavy-lift airships [28]. In the 1980s a hybrid heavy-lift vehicle named *Aerocrane* was designed featuring a spherical, helium-filled centerbody with rotating wings mounted on the equator of the spherical body. Engines were installed at the tips of the rotating wings, and a non-rotating gondola was attached below the sphere. A one-tenth scale dynamic model of a 50-ton payload was built to investigate the stability and control characteristics [29]. The heavy-lift airship dynamics was studied using a test vehicle. The large thrust-to-weight ratio and low fineness ratio of heavy-lift airships resulted in strong nonlinear rotor/hull aerodynamic interactions, making heavy-lift air vehicles quite different from classical airships. Small perturbation dynamics, effect of payload on system dynamics, and effect of flight speed on vehicle dynamics were also studied [30].

In recent years, many projects have been proposed for the design and development of new heavy-lift air vehicles. The US *DARPA* Walrus project [31,32] was aimed at carrying 500 tons over intercontinental distances. Although this project was not completed, the hybrid approach was put forward to combine lighter-than-air buoyancy and aerodynamic and propulsive methods in lift generation. The thick cambered-section twin-hull design of the ATG heavy-lift airships, *SkyCat* Series, (Fig. 16) produces large aerodynamic lift in forward flight and therefore provides high payload capability. The *SkyCat* Series can operate between 8% light and 40% heavy in contrast to 5% light and 8% heavy of conventional airships (www.worldskycat.com). The *SkyCat-220* is equipped with unique retractable hover-cushion engines, which enable vertical takeoff and landing capability and eliminate the need for ground handling [17,33]. The Boeing Company and *SkyHook* of Calgary, Alberta, began developing the heavy-lift airship *JHL-40* in March 2008 [34]. Its payload is carried by four helicopter rotor systems and the vehicle's empty weight is supported by the neutral buoyancy of the airship. The Canadian company *Millennium Airship* participated in the design and development of *SkyFreighter*, which is capable of transporting a large cargo anywhere in the world safely, quickly, and at low cost. In June 2008, a unique hydrogen fuel system was developed by *Millennium Airship.* Hydrogen was chosen as a replacement for Jet A fuel and a hydrogen fuel system can be accommodated in hybrid heavy-lift airships (www.millenniumairship.com/LatestNews.htm). It should be noted that heavy-lift air vehicles can be designed to have non-rigid or rigid configurations. Most of the above-mentioned heavy-lift air vehicles have non-rigid hulls while the *Aeroscraft* employs a rigid-hull design.

3.5. Other unconventional designs

There have been attempts of utilizing unconventional materials to build buoyancy air vehicles. Smart materials/active

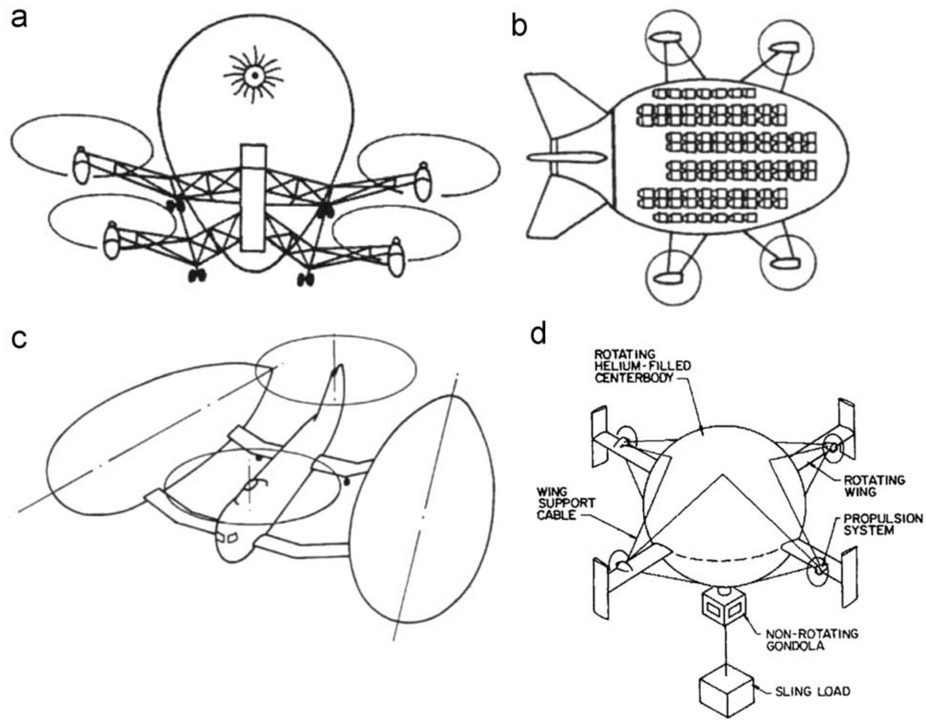

Fig. 15. Heavy-lift air vehicles (*Source*: Ref. [1]). (a) Piasecki Heli-Stat, (b) Helitruck, (c) Heliship, and (d) Aerocrane configuration.

materials have been employed in the construction of intelligent components of airships. Active materials can sense and respond to external stimulus and environment, and this remarkable property is especially useful for structures requiring deformation recovery. Smart materials for this application include shape memory alloys, piezoelectric materials, dielectric elastomers, etc. With the inclusion of smart materials, inflatable and rigidizable wing components can be added to airships to allow for the change of volume, storage, and recovery [35]. Smart landing gears made of super elastic shape memory alloys, carbon composites, and natural canes have been developed for semi-rigid airships. Shape memory alloys have unique characteristics of large energy dissipation, which ensure the suppression of shock and vibration, for example the absorption and reduction of the impact energy during landing [36]. Also, a biologically inspired propulsion system for blimps based on dielectric elastomers has been proposed. Planar dielectric elastomers are integrated into the envelope in order to deform the rear lifting body and, arranged as active hinges, in order to flap an aft-tail. The dielectric elastomers act as actuators in order to provide the necessary active strains for specified body deformations [37].

Innovative pneumatic structures have been proposed to construct unconventional airships with lenticular, deltoidal, or winged-hull shapes. Connecting hollow tubes stiffened by internal pressure to the airship envelope made it possible to relate the air pressure to the envelope deformation. This unique approach was found beneficial for overall weight reduction and structural reinforcement [38].

Significant research has also been conducted to develop solar-powered high altitude and stratospheric airships. *Lockheed Martin Maritime Systems & Sensors* designed a high altitude airship prototype with a length of 500 feet and a diameter of 150 feet [39] (Fig. 17). The *United States Army Space and Missile Defense Command* designed and flight tested the *HiSentinel* stratospheric airship model CHHAPP in order to demonstrate the engineering feasibility and potential military utility of an unmanned, untethered, gas-filled, solar airship flying at an altitude of more than 60,000 feet [40] (Fig. 18). The airship development projects conducted in recent years are summarized in Table 1.

4. Modeling, analysis, and optimization

Several research studies have been carried out on dynamic modeling and flow simulation of airships. Dynamic models are built to study control techniques of airships (control of trajectory, stability, and maneuverability). Li et al. [41] developed a linear model for flexible airships which was used to study structural flexibility effects on airship flight dynamics and aerodynamics. The flight simulation of blimps requires an efficient physical dynamic modeling and parameter identification procedure. Zufferey et al. [42] employed a pragmatic methodology to simplify parameter identification without costly and lengthy wind tunnel testing. The airship aerodynamic performance was studied by computing the flow over airship bodies using computational fluid dynamics [43–45]. Three-dimensional boundary layer separation has a decisive influence on the pressure distribution and on the aerodynamic load and moment distribution of airships. Therefore the identification and determination of flow separation is of extreme importance. Boundary layer methods were applied to determine the location of flow separation on an inclined airship hull at large angle of attack. A finite volume method was used for the numerical simulation of low Mach compressible flow around a generic airship [46]. The challenges posed by the computation of turbulent flows were addressed by Omari et al. [47] who investigated the effect of three different turbulence models on the prediction of separation-induced vortices on airships flying at large angle of attack.

Although the research on dynamic modeling and flow simulation is of vital importance, we concentrate in this review on the structural modeling and analysis of airships. Additionally, the optimization of airship bodies will be covered.

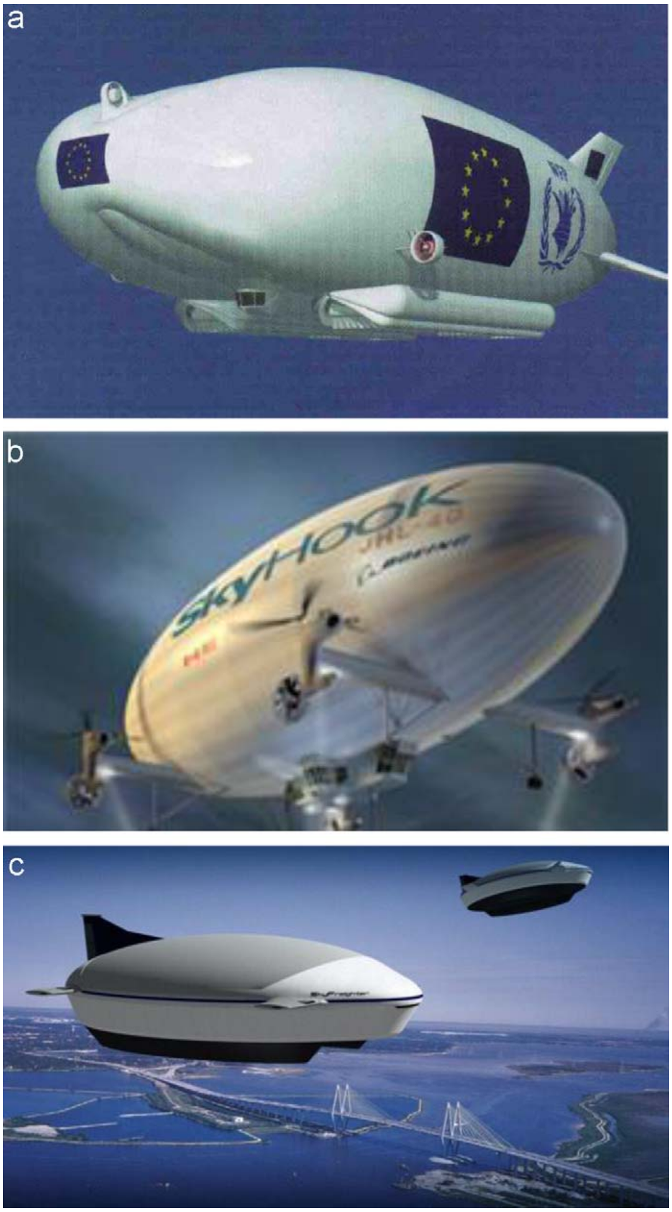

Fig. 16. Heavy-lift air vehicles. (a) SkyCat Series (*Source*: Ref. [17]), (b) Heavy-lift aircraft JHL-40 (*Source*: www.skyhookhlv.com), and (c) SkyFreighter (*Source*: www.millenniumairship.com).

Fig. 17. Lockheed Martin high altitude airship (*Source*: www.lockheedmartin.com).

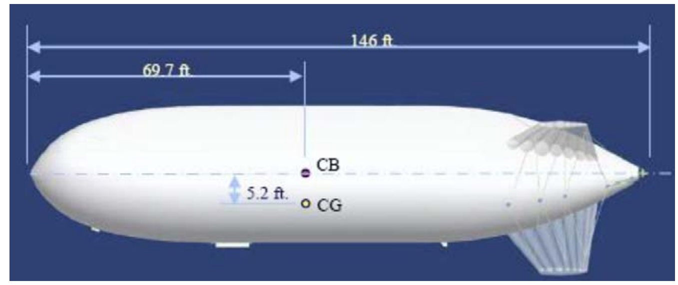

Fig. 18. HiSentinel airship CHHAPP (*Source*: Ref. [40]).

4.1. Structural modeling and analysis of non-rigid airships and semi-rigid airships

Substantial efforts have been devoted to the study of non-rigid airship structures [48,49]. Empirical methods have been employed in the design and analysis of hull shape and principal structural components including fins (rudders, elevators, and canards), gondola, nose structure, engines, landing gears, etc. Two books [1,10] serve as classical reference publications for airship design and analysis. For preliminary analysis, an airship can be treated as a loaded beam subjected to bending forces from unequal distribution of weight and buoyancy along the length of the body. Weight, buoyancy, and shear forces are calculated by dividing the airship body into many longitudinal segments. The computation of the static bending moments can be separated into three parts: vertical forces of distributed weight and buoyancy, longitudinal components of suspension rope tension, and longitudinal forces due to increase of gas superpressure [10]. The contribution of the gondola weight is included in the first two parts. The aerodynamic bending moment can be computed from the effect of the empennage lift and transverse forces on the envelope (using Munk's momentum theory). For a preliminary calculation, the maximum aerodynamic bending moments $M_{\max}$(lb-ft) can be obtained from the empirical formula [1]

$$M_{\max} = 0.029[1 + (L/D - 4)(0.5624L^{0.02} - 0.5)]\rho\,\mu V_{\infty} Vol L^{0.25}$$

where μ is the gust velocity (ft/s), V_{∞} is the airship equivalent speed (ft/s), ρ is the air density (slugs/ft^3), *Vol* is the total envelope volume (ft^3), L is the length of the airship (ft), and D is the maximum envelope diameter (ft). The maximum aerodynamic bending moment in the envelope occurs near the airship center of gravity. In general, the aerodynamic bending moment exceeds the static bending moment.

It should be noted that the envelope is the load-bearing structure for non-rigid configurations and its material property determines the airship strength. On one hand, the envelope fabric should be strong enough to bear stress without bursting; on the other hand, sufficient tension forces generated by internal pressure are required for keeping shape and maintaining total structural integrity. The envelope loads include the static loads from buoyancy and component weight and the superpressure of the lifting gas, and the dynamic loads under all operational conditions. The Federal Aviation Administration *Airship Design Criteria* [50] specify the strength requirements for the envelope of non-rigid airships with a high safety factor. For a fixed length to diameter ratio the surface area of the envelope for non-rigid airships increases with the square of the diameter. The hoop stress of the envelope is proportional to the envelope diameter, which mandates a large fabric strength for large airships [6]. The maximum size of a non-rigid airship depends on the fabric seam strength of the envelope and the limit design pressure. The

Table 1
Summary of airship projects in recent years.

Designer	Model	Unique features	MaxO altitude (ft)	Max. speed (mph)	Country
ATG/World SkyCat	Skycat-20	VTOL and cargo aircraft	10,000	97	UK
Skyhook–Boeing	SkyHook JHL-40	Heavy lift four rotor and 40-ton lifting capacity	N/A	80	Canada/US
Lockheed Martin	HAA™	Solar-powered, high altitude, unmanned, and un-tethered	60,000	28	US
Techsphere Systems International	SA-60	Spherical shape and low altitude	10,000	35	US
Southwest Research Institute	HiSentinel Airship	Stratospheric and solar-powered	$>$74,000	N/A	US
21st Century Airship Inc.	N/A	Spherical shape	Low altitude	35	Canada
Millennium Airship Inc.	SkyFreighter	Hybrid, heavy lift, and VTOL	20,000	80	Canada/US
Ohio Airships Inc.	DynaLifter PSC-3	Winged hybrid, VTOL, and heavy lift	10,000	115	US
Zeppelin Luftschifftechnik Gmbh	Zeppelin LZ NT-07	Semi-rigid, internal rigid framework consisting of carbon fiber triangular frames and aluminum members	8203	80.8	Germany
LTA Corporation	Alize 50	Lenticular shape, semi-rigid, and VTOL	6562	81	France
AEROS	Aeroscraft ML866 model	Control of static heaviness, heavy lift, and VTOL	10,000	115	US

maximum theoretical envelope size of non-rigid airships continues to grow as stronger fabrics and seams are developed [51].

As early as 1982, finite element methods (FEM) based on small deformation theory were used to analyze the structural behavior of aerostats for various configurations and loading conditions. In this NASTRAN model, bar, rod, and plate elements were utilized and an equivalent elastic modulus was obtained to convert the internal suspension system to a series of ropes running from the confluence point to the hull patch. This approach provided some basic modeling techniques for the finite element analysis (FEA) of airships [52]. A nonlinear FEA MSC/NASTRAN code was also developed in the 1980s [53] to study the static and dynamic behaviors of non-rigid airships by modeling the major structural components of envelope, suspension system, and nose battens. The commercial finite element software ABAQUS was employed in a geometrically nonlinear analysis of a non-rigid airship envelope. In this work load distribution and structural reserves were optimized by adjusting the internal suspension system [54]. The distinctive advantage of ABAQUS is that it can deal with nonlinearity associated with large deformation and material property [55]. Further, FEM was applied to analyze deformation modes of flexible airships [56]. Nonlinear FEA employing triangular membrane elements was implemented for the structural analysis of stratospheric airships [57]. The interactions between pressurized envelope and attached nose cone, keel, and empennage for a semi-rigid airship CL160 were analyzed by FEM parametric studies [58]. This study showed that the layout of the internal suspension system had the most significant effect on the distribution of the static bending loads between keel and envelope. It showed that the basic loads emerging from weight and buoyancy lift can be supported by the envelope alone.

It should be noted that stratospheric and high altitude airships employ lighter-than-air non-rigid configurations. Much effort has been put into the modeling and analysis of stratospheric and high altitude airships in recent years [59–65]. Weight optimization of unmanned airships operating in an extreme environment at high altitudes presented a challenge, especially the optimal design of an ultra-lightweight hull. At high altitudes, a large volume airship body and a light-weight envelope and components are required, in order to produce enough lift and payload. The selection of shape and volume, weight, cost, propulsion power, payload, and operating capability have been integrated in the optimization of non-rigid airships at high altitudes [63–65].

Some critical issues need to be addressed in simulation and analysis of non-rigid airships. First, unlike airplanes and helicopters, aerostatic lift needs to be considered for buoyancy air vehicles. Center of buoyancy, center of gravity, and their relative location are essential for airship balance and performance. Second, due to its large surface area relative to its mass, an airship experiences the effects of a larger mass than the actual airship mass during acceleration and deceleration. In load analysis of flight maneuver conditions, virtual longitudinal mass, virtual transverse mass, and virtual moment of inertia can be obtained by multiplying the original parameters by virtual inertia coefficients longitudinally, transversely, and rotationally. Third, for numerical simulation, finite element programs should be able to deal with nonlinear problems relevant to large displacement of the envelope fabric and tension-only members. Membrane elements are usually used for the modeling of laminated composite fabric. The connection between different types of elements needs to be carefully addressed since there are interactions between hull and fins and interactions between hull and structural components. Fourth, the pretension forces of structural members have an important effect on simulation and analysis results, which should be prudently considered.

4.2. *Structural modeling and analysis of rigid airships*

The first investigation of rigid airships can be traced to the 1920s. A general theory for the calculation of primary and secondary stresses of rigid airships was described and used in the investigation of the Navy's ZR-1 by the special subcommittee of the *National Advisory Committee for Aeronautics* [66]. Use of the rigid airship concept for future naval operations was proposed in 1978 [67]. Woodward [68] compared and discussed various bulkhead constructions in 1982 and investigated the effect of pretensions of structural members and cables on the loading and strength of bulkheads. He also solved the equation of equilibrium of loaded wires for free-center bulkheads and fixed-center bulkheads [69]. Cox [70] classified the external forces on an airship structure according to system components and airship status. *The National Aerospace Laboratory NLR* developed a basic flight simulation tool for a generic large rigid airship. This tool built with Matlab/Simulink in a PC-based desktop environment covered the simulation of the complete hull. Equations with six degrees of freedom were employed and models for aerodynamics, buoyancy, mass and inertia including virtual mass, and engines were utilized. Simulation possibilities in various phases of the design process were evaluated. This simulation tool can be used for the understanding of the dynamic behavior of rigid airships with different configurations (i.e. three or four fins, engine positions, stretching the body, etc.) [71]. Also, the wreck of the rigid airship *USS Macon* was investigated recently [72].

In modeling and simulating rigid airships the envelope is not a critical structural member, but the size and spacing of the transverse and longitudinal girders are vital considerations. These girders are reinforced by a complex system of wiring or cables. These tension-only members provide the shear and torsion strength of the airship external frame and improve the transverse rigidity of the bulkheads as well. For the conventional rigid airship design, the design of the girders and bulkheads usually relies on the past experience of the designers or on structural testing. The early analysis of the longitudinal and transverse strength of rigid airship frames and design guidelines can be found in *Airship Design* [10]. Based on the authors' knowledge, the modern numerical modeling of rigid-hull structures has rarely been reported in archival publications. Research on accurate and efficient structural analysis and optimization of structural members therefore is highly needed for rigid airship development.

4.3. Optimization

Design optimization of an airship system is a complicated procedure because it is associated with the disciplines of structural mechanics, flight mechanics, aerostatics, aerodynamics, manufacturing, etc. Airship optimization involves many aspects and parameters, such as weight, size, shape, materials, flight path, manufacturability, maneuverability, energy consumption, and special functional features. For most cases, an iterative strategy might be used for the optimization procedure. A variety of parameters can be selected as optimization objectives, such as minimum weight without the loss of structural integrity, and optimal shape with minimum drag. In 1969, the volumetric characteristics, takeoff, cruise, and landing characteristics were selected as optimized targets in analyzing the efficient and optimal design of buoyant-type air vehicles [73]. In order for an airship to fulfill the mission of observation and detection, precise flight path control is required. The optimization of flight trajectories from a given initial location to a desired final destination is usually formulated as a nonlinear optimal control problem. It was found that the trajectories vary for different optimal flight objectives (such as minimum flight time, distance, energy consumption) [74].

Optimization of airship body shape can reduce the aerodynamic drag and improve airship performance. Shape optimization of an airship envelope under the constraint of specified volume was performed based on the distribution of pressure and airship surface velocity generated from an improved panel method [65]. The problem was also posed as a multi-disciplinary optimization problem, and a computational fluid dynamics code was developed to accommodate the mathematical model for envelope drag estimation [75,76]. Shape optimizations of axisymmetric airship bodies with the objective to minimize the drag for a given envelope volume and an airship speed range were undertaken for different Reynolds number regimes that cover all airship applications [77]. Reynolds number has a significant effect on the optimal shape. This was demonstrated by the drag curve for optimal body contour at five design regimes (Fig. 19). Moreover, an effective and powerful optimization procedure (Genetic Algorithms) has been combined with an aerodynamic calculation method to compute

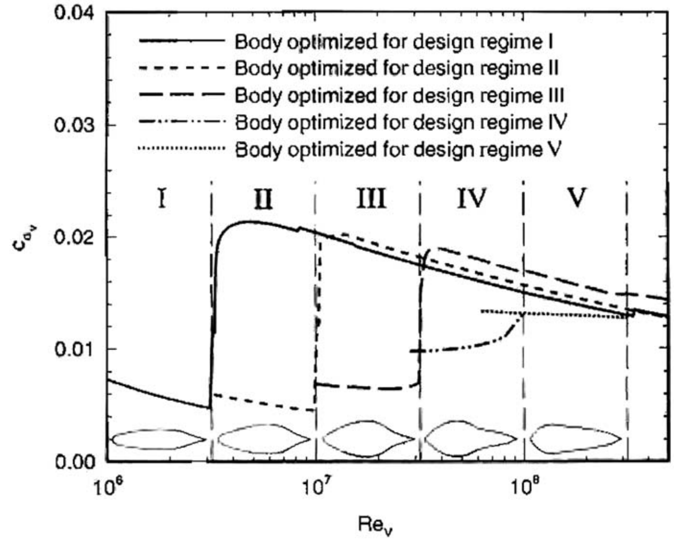

Fig. 19. Drag curve of the optimized body shapes (*Source*: Ref. [77]).

the drag coefficients for different Reynolds number regimes and to optimize airship-hull shape [78,79]. Genetic Algorithms was proved to be an efficient method for such a multi-dimensional, multi-modal, and nonlinear objective function. A multi-objective decision-making method was employed in envelope shape optimization of a certain airship. This approach took into account unavoidable deviations, selected preference information, and eliminated certain possible optimization solutions violating constraint conditions [80].

5. Summary

Starting with a historical introduction, the developmental status of conventional non-rigid, semi-rigid, and rigid airships and of unconventional airship-type air vehicles was reviewed. Unconventional hull configurations, such as spherical, lenticular, multiple hull, and winged shapes, and other distinctive features, such as unique lifting gas, hybrid operation mode, and high payload capability, were discussed. The unique characteristics and applications of modern airships developed in recent years were summarized. Furthermore, the airship-relevant structural modeling, analysis, and optimization techniques were outlined.

This review showed that the incorporation of technology advances in high-strength materials, structures, aerodynamic modeling, analysis, and simulation techniques makes it possible to develop modern buoyancy air vehicles that are more capable, more reliable, stronger, safer, and more versatile than their predecessors. They provide a unique means of air transportation which has generated interest for use in unmanned surveillance and manned logistic missions [81]. Continued research and development work makes it likely that airships will see a major comeback.

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