COMMAND AND STAFF TRAINING INSTITUTE
BANGLADESH AIR FORCE

Individual Staff Studies Programme (ISSP)

PROFESSIONAL-2 : FLYING AND AIRMANSHIP FOR PILOT
PHASE-16 PART-II

PROFESSIONAL-2 : FLYING AND AIRMANSHIP FOR PILOT PHASE-16 PART-II

First Edition : October 2011

Revised by : **Gp Capt Md Shafiqul Alam, psc GD(N)**

Wg Cdr Khan Md Mahmudul Huq, psc GD(P)

Approved vide Air HQ/10066/Air Trg//Vol-46/64A Date 18 Jan 2011.

CONTENTS

PHASE-16, PART-II
CONDUCT OF THE PHASE
SUBJ : PROFESSIONAL SUBJECT-2 (FLYING AND AIRMANSHIP FOR PILOTS)

Weeks: 08 **Period: 80**

Ser No	TOPIC		Pd Distr	Total Pd
1	**Meteorology**			12
	Sub Topic	Thunderstorm	6	
		Monsoon	4	
		Cloud	2	
2	**Basic Principles of Flights**			19
	Sub Topic	Lift Augmentation	6	
		Flight Control	9	
		Climbing and Gliding	4	
3	**Basic Principles of Helicopter Flight**			12
	Sub Topic	Control in Forward Flight	8	
		Autorotation	4	
4	**Supersonic Aerodynamics**			9
	Sub Topic	Transonic and Supersonic Aerodynamics	9	
5	**Navigation**			13
	Sub Topic	Alteration of Heading	7	
		Adjustment of Timing	6	
6	**Revision and writing the TAE Paper**			15
			Total Period =	80

INTRODUCTION TO THE PHASE

Scope of the Phase

1. Phase-16 Note (Part-II, ISS) is a self-contained précis. It contains part of the following subjects:

   a. Meteorology

   b. Basic Principles of Flights

   c. Basic Principles of Helicopter Flight

   d. Supersonic Aerodynamics

   e. Navigation

2. The syllabus has been so designed that you would be able to co-relate and implement (most cases) your knowledge in the profession field.

TOPIC-1 : METEOROLOGY

THUNDERSTORM

Introduction

1. The thunder is the noise of lightning discharge and it is noticeably delayed if the lightning is at a considerable distance, owing to the great difference between the speed of light and the speed of sound. The distance of a lightning flash may be roughly estimated from the interval between seeing the flash and hearing the thunder, counting one mile for every five seconds. The thunderstorms are defined in terms of the electrical manifestations. From the more general meteorological point of view, this definition may be regarded as based only on a rough measure of the size and intensity of a cumulonimbus cloud system.

Aim

2. To know about the most furious weather phenomena, thunderstorm, in detail.

Definition

3. The sound produced by the electrical flash of a cumulonimbus cloud is known as *thunder* and the associated weather like hail, shower, squall, turbulence etc are called *storms*, and both thunder and storms are jointly known as thunderstorms. By agreement in the WMO, a thunderstorm is reported if thunder is heard at the station.

Favourable Physical Conditions for Formation of Thunderstorms

4. The favourable atmospheric conditions necessary for the formation of thunderstorms are:

a. Atmosphere must be unstable throughout a deep layer preferably upto tropopause.

b. Moisture content of unstable layer should be high, particularly in the lower level.

c. An initial triggering action is to set up the vigorous convection. The triggering actions are:

(1) Insolations (Incoming Solar Radiation, ie Sun's ray).

(2) Convergence of winds at lower levels.

(3) Vertical lifting of air due to depression, cyclone etc.

(4) Katabatic flow.

Types of Thunderstorms

5. In general, thunderstorms have the similar physical features regardless of location and time. However, they do differ in intensity, degree of development and associated weather like hail, turbulence, squally wind, electrical discharge etc. Thunderstorms are generally classified according to the manner in which the initial lifting action is accomplished. The different types of TS are:

a. Air mass or heat thunderstorm:

(1) Convective thunderstorm.

(2) Orographic thunderstorm.

(3) Nocturnal thunderstorm.

b. Frontal thunderstorm:

(1) Warm front thunderstorm.

(2) Cold front thunderstorm.

(3) Squall line/pre-frontal thunderstorm.

(4) Occluded thunderstorm.

Air Mass or Heat Thunderstorms

6. The basic characteristics of air mass TS are that they form within a warm and moist air and are no way associated with fronts, and they are generally isolated and scattered over large area. Over land they tend to reach maximum activity in the afternoon and evening and die out at night. Over the Sea, they show little or no diurnal variations. The air mass or heat TS are classified as:

a. **Convective TS**. Convective TS occurs over land or sea in most of the areas of the world and very common in the temperate zone during the summer months. Their activities reach maximum in Bangladesh during the pre-monsoon period. The initial lifting action for these TS is provided by the convective current produced by the heating of the lower layers of the air in contact with the warm land or water masses. They normally form over land during afternoon when the earth receives the maximum heat from the sun. When the air is very unstable and moist, the cu cloud may develop into TS. This type of TS also forms over coastal regions during afternoon, when cool and moist air is heated as it moves over the warmer land surface. Convective TS is the most common one in Bangladesh.

b. **Orographic TS**. Orographic TS forms when moist unstable air is forced aloft by mountainous region/terrain. They tend to be more frequent during afternoon and early evening because heating from below is working in conjunction with the forced lifting. The storm activity is usually scattered along the individual peak of the mountain, but occasionally there will be a long unbroken line of TS. Violent TS with hails are common in high mountains. Identification of orographic TS from the windward side of the mountain is often difficult because st and sc clouds below the level of free convection (LFC) frequently enshroud (covered) the mountains and obscure the storm clouds. Orographic TS are common in mountainous areas of Bangladesh.

c. **Nocturnal TS**. Due to the diurnal variation of temperature ie radiational cooling, TS occurs during night and early morning, these TS are called nocturnal TS. These are associated with the cooling of moist air aloft, but the mechanism set off their formation is not yet well understood. TS during pre-monsoon period which develops during night and early morning over northern and northeastern part of Bangladesh and moves usually towards south may fall in this category.

Frontal Thunderstorms

7. Frontal TS usually occurs where a cold air mass undercuts a warm air mass, that is at a cold fronts; although occasionally from warm front. They occur along a line of front and cannot easily be avoided. The Cb cloud is often masked by other frontal clouds. Frontal TS are associated with surface and under fronts. Frontal TS are less observed in Bangladesh. The different types of frontal TS are:

a. **Cold Front TS**. The lifting of warm air at a cold front may be sufficient to produce TS if the warm air is sufficiently unstable, specially the cold front is fast moving and has a steep slope. This storm may occur at any season. Pure cold front TS occurs very rarely in Bangladesh.

b. **Warm Front TS**. Due to less steeper slope of the warm front the air mass tends to rise less rapidly at a warm front, and consequently this types of TS is much less common than the cold front type. The Cb cloud in warm front TS are sometimes marked by layer clouds, and it is then possible to come upon active storms without warning.

c. **Occluded Front TS**. TS associated with occlusions, or with front not evident at the surface but clearly defined aloft, are usually similar to one of the types already described. They are more common in subtropical than temperate latitude. TS in Bangladesh during pre-monsoon period and post-monsoon period are, at times, aggravated by the passage of these fronts.

d. **Squall Line TS.** As squall line TS often develops about 50 km to 300 km ahead of and roughly parallel to fast moving cold front so they fall under the frontal TS. Some times squall line TS occur without accompanying front, and with accompanying troughs, ITCZ, shear lines or lines where sea breezes converge against mountain barrier; as such, they are categorized under another types of TS, Squall Line TS. It is difficult or impossible to cross the Squall Line TS without entering the Cb clouds. The cloud bases are often lower and tops are higher than the most TS. The most severe conditions, such as heavy hail, destructive winds and tornadoes are associated with the squall line TS. The steering of squall line TS movement is in the direction of 500mb winds and 40% their speed.

There is another type of TS, isentropic TS, which occurs as a result of isentropic vertical displacement of a convectively unstable air mass. This may be associated with warm front or nocturnal TS in many cases.

Life Cycle of Thunderstorms

8. **Thunder Cloud.** A thundercloud or cumulonimbus (Cb) cloud is composed of several cells each of which behaves as a unit of convective circulation and goes through its life cycle of 20 minutes to 1½ hours duration more or less independently of adjacent cells. The diameter of individual cell varies normally from 1 mile to 5 miles and rarely from 5 miles to 40 miles; while between neighbouring cells there are cloud filled lanes upto 1½ miles in width. TS develop in clusters of two or more. The clusters, individual cells of TS at various stages of development, may be over a hundred miles in diameter and last for 6 hours or more.

9. **Description of Thunder Cloud**. It is convenient to discuss the individual thundercloud for the structural characteristics on the basis of 3 stages of its life cycle. The 3 stages of thundercloud are:

a. Cumulus or initial stage.

b. Mature stage.

c. Dissipating stage.

10. **Cumulus Stage**. The initial stage of thundercloud or TS is always cumulus (cu) cloud or a collection of cu cloud. The main feature of this stage is the ‘updraft’ throughout the cloud. The top of the cloud generally extends up to 15,000 feet; in some cases may extend upto 30,000 feet after which water and ice particles grow large enough to give radar echo. The updraft motion within the cloud may vary in strength from place to place and minute to minute. The greatest vertical speed of 3,000 feet per minute or more occurs at higher altitude late in this stage. Air enters into the cloud all the sides, this process is called *entrainment;* the cumulus stage lasts for about 15 minutes. In the meantime large amount of cloud droplets or snowflakes accumulate in the cloud. Eventually, the amounts of accumulated water become so large that the heavier elements cannot be supported by the updrafts; water then begins to fall through cloud. The frictional drag exerted by the falling water turns the updraft into a downdraft, and a heavy downpour sets in, making the beginning of the mature stage. The cumulus stage of TS is shown in Figure 1.

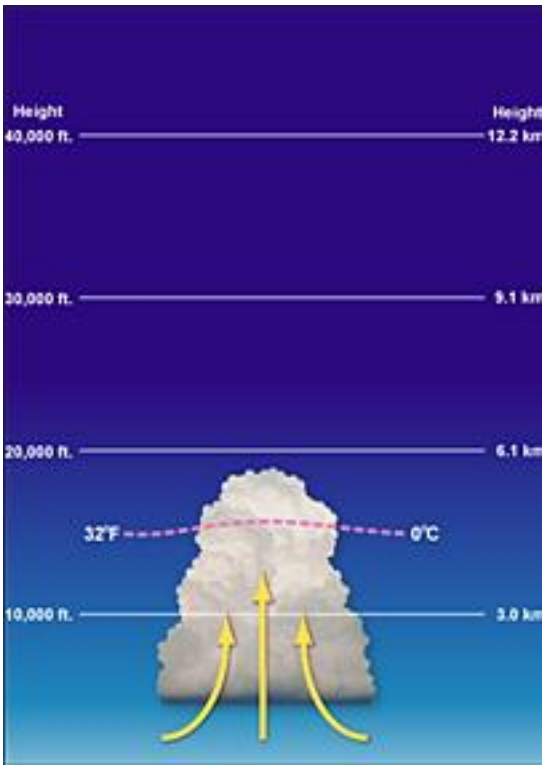


Figure 1a: Cumulus stage of TS

Figure 1b: Cumulus cloud

11. **Mature Stage.** The main characteristics of the mature stage are that it has updraft and downdraft side by side. It begins when rain first falls distinctly out of the bottom of the cloud. Except under arid conditions, the rain reaches the ground. The region of organized downdraft occurs in the central forward portion of the cloud, and they gradually increase first in-depth and then in horizontal extent. Their speeds vary and may reach 2,500 feet per minute. In the lower 5,000 feet of the atmosphere the speed of the downdrafts decrease due to barrier presented by the earth's surface and cause the downdraft to spread horizontally near the surface. The onset of the downdraft at the ground is usually sharp and marked by strong gusts. The average duration of mature stage is about 15-30 minutes and the average vertical depth may reach 40,000 feet and in exceptional case may reach to

60,000 feet in tropical areas. Hails occur during the mature stage in many but not all storms and grow in concentric zones from particles being carried cyclically above and below the freezing level (FL). As the top of the cloud reaches the layer of stable atmosphere so it spreads horizontally, or upper air jet may flatten out the upper portion of the cloud into the well-known ‘Anvil Top’ from which pseudo cirrus cloud may be blown. This stage continues till the updrafts remain higher or equal to the downdrafts. The mature stage of TS is shown in Figure 2.

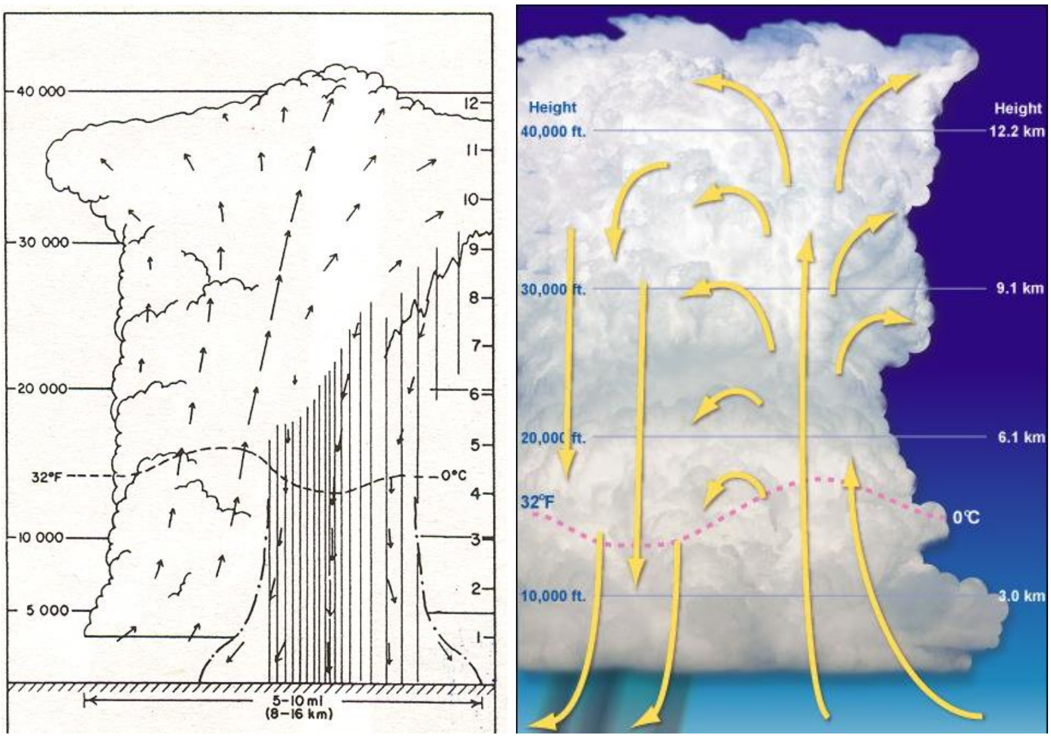


Figure 2: The mature stage of TS.

12. **<u>Dissipating Stage</u>**. The dissipating stage is characterized by the downdrafts gain over the updrafts. In this stage the entire TS ultimately becomes an area of downdrafts. Dissipation results from the fact that there is now no longer the updraft source of condensing water. Because of heating and drying process produced by the downdrafts, the rainfall gradually ceases, and eventually cloud dissolves or disintegrates into irregular lumps of scud at low levels and dense patches and streaks of anvil cirrus at high levels. The dissipating stage of TS is shown in Figure3.

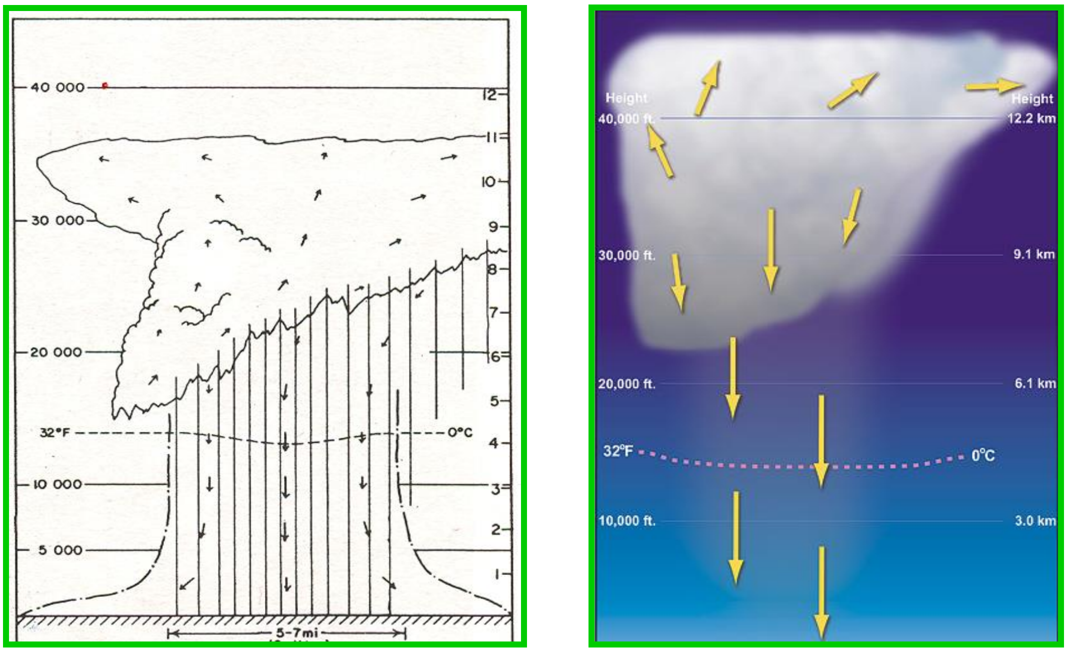


Figure 3a: The dissipating stage of TS

Figure 3b: The dissipating stage of a thundercloud with anvil shape

Thunderstorm Structure

13. The cellular structure and life cycle described above envisages three stages of evolution. The life cycle of an individual cell lasts about an hour. However, observations show that in severe storms, the mature stage may last much more than an hour. The cell at the mature stage gets continually revived, developing into a super-cell with updraft and downdraft co-existing in a more or less steady state for periods lasting over an hour. There is strong vertical wind shear in such storms. Energy is provided by the absorption of latent heat from the partial evaporation of the precipitation within the dense, cool dry high- level air which sinks as the downdraught and undercuts the warm, moist updraft at the rear of the storm. The updraft extends some kilometers beyond the tropopause and gives rise to unusually high-domed tops.

Electric Field

14. In clear air of normal density a critical electrical field of about 3,000,000 volts per metre is required for breaking down the insulation and for a spark to pass. In cloud it is reduced to about 1,000,000 volts per metre. Such intense electrical fields are built up locally within a Cb cloud. The upper portions of a Cb cloud acquire a positive charge and the lower portions a negative charge. The exact cause of the generation of these charges is not yet fully understood. However, the electrical field is sufficiently strong to permit a lightning discharge. Discharges may take place within the same cloud, from one cloud to another and less frequently from cloud to the earth. The lightning discharge is in the form of stepped strokes, 1 to 4 km long with a channel diameter of 1 to 10 metres.

15. The air through which the discharge has passed is rendered white hot and expands suddenly, giving the clap of thunder. If the lightning stroke is long, the thunder may be in the form of peals as the sound from different parts of it takes longer time for travel and reach the ground.

Movement of Thunderstorms

16. Although large thunderstorms modify the airflow in their immediate neighbourhood, most thunderstorms drift slowly with the wind prevailing in the layers in which they are embedded. As a first approximation, the direction of movement may be deduced from the prevailing winds at 3 to 5 km above sea level. The speed of movement is less than the speed of the wind at these levels. When the winds aloft are weak or variable, thunderstorms show little movement. In such cases the shower from the cloud is confined to a limited area, resulting at times in exceptionally heavy falls of short duration, popularly known as *cloudburst*. If the thunderstorm has appreciable movement in the rain stage, the shower gets distributed over a larger belt.

Vertical Extent of Cumulonimbus Clouds

17. From radar surveillance as well as aircraft report it has been found that Cb clouds over the Indian region reach great heights, at times upto the tropical tropopause. Average heights of tops are between 10 and 15 km. Cb clouds have, however, been reported to reach heights of 18-20 km. The base is usually over 1 km above ground, but in heavy showers may lower to less than 300 metres above ground in the monsoon season.

Flying Hazards of Thunderstorms

18. Thunderstorms pose a variety of hazards to aircraft in flight. The more important ones are listed in the following:

a. **Squall, Wind Shear and Microburst**. Squall means sudden increase in wind speed and possibly change of direction. Squalls from thunderstorm wrecked mariners for centuries before aviation commenced. Flying has led to a continuing study of such airflow and yet its pattern cannot be precisely forecast or measured despite an intense study setup by ICAO in 1977. Major airports issue wind shear alerting messages and pilots are expected to report any wind shear experienced. Sometimes the normal variation of wind speed with height becomes greatly accentuated, perhaps decreasing from 40 knots or more at 1,000-2,000 feet to less than 10 knots near the surface. A varying cross wind component complicates the matter. The gust front of self-propagating storms may be 15 to 20 km ahead of the storm, which generated it. It may be marked by newly forming cumuliform clouds or by a line of duststorms in desert countries, but equally it may be quite invisible. Microbursts are particularly intense and localized, probably not more than half a km across, and especially hazardous when they are overhead or near the runway in use. Again, if on the approach in thunderstorm conditions it is found that abnormal levels of power are necessary to maintain the airspeed, attitude and glideslope, then wind shear go-around should be initiated. The US Federal Aviation Administration (FAA) initiated the ‘low level wind shear alert system (LLWAS)’ at major US airports where wind shear problems are a frequent hazard. LLWAS detects not only microburst but also any hazardous wind shear.

b. **Heavy Showers**. These may reduce ground visibility to very low values for short durations.

c. **Fractostratus Clouds**. These clouds are actually ragged fragments of the base of the Cb; the fragmentation occurs due to turbulence caused by the squall in the region between the ground and the cloud base. At times the base of these fragments may be as low as 500 ft even over comparatively plain ground.

d. **Poor In-flight Visibility**. In the interior of a Cb cloud the in-flight visibility is practically nil. Cb clouds have a larger amount of water content per unit volume as compared to other clouds, both the concentration as well as the size of drops being higher.

e. **Drafts.** Within the cloud the strong up-drafts and downdrafts may cause sudden and large variations in the altitude of an aircraft. In general, the updrafts are stronger than the downdrafts, both being predominant in the middle and upper parts of the cloud. In the thunderstorm project in USA the traverses were made at cruising speed of about 160 kt. The highest vertical displacement encountered was 6,000 ft in the upward direction and 1,400 ft in the downward direction, both at a flight level of about 25,000 ft. The storms traversed were of the sub-tropical variety. It is possible that in summer thunderstorms in the tropics the displacements may be of a somewhat higher order.

f. **Gusts**. Near the borders of the updrafts and downdrafts the large difference in the velocities creates friction. This friction is responsible for vigorous eddies which, once formed, travel horizontally with the wind and also in the vertical direction with the draughts. They are mainly responsible for the extreme bumpiness within the cloud, although the effect of the draughts is also mixed up. The severity of bumpiness increases with height upto the middle part of the cloud and remains constant upto about 10,000 ft below the top. Further aloft it decreases rapidly. Bumpiness is much less in the (cloud-filled) lanes between two adjacent cells of the same storm.

g. **Ice Accretion.** The formation of ice on the parts of an aircraft in flight is known as "ice accretion" or merely as 'icing". Icing can affect the aerodynamics of the aircraft even upto the stage of loss of control. It is thus a serious hazard requiring careful study of the different types of icing, the meteorological conditions under which they occur and the techniques of flying which avoid or minimise the risk of icing. Although many types of aircraft are fitted with de-icing equipment, this provides only partial protection and its successful operation is facilitated by knowledge of the type of icing and the possible rate of accumulation.

h. **Hail**. Aircraft which encounter hail in flight, can suffer serious damage. There have been instances wherein airframes have been badly dented, windscreens holed. Perspex astrodomes shattered, de-icing boots ripped off and radiator found badly bent. Other things being equal the damage is more in the case of faster aircraft.

j. **Lightning.** Apart from distracting aircrew and temporarily dazzling their eyes lightning may interfere with radio communication and may seriously affect the magnetic compass performance. The aircraft itself does not, however, get damaged due to lightning strike.

Avoidance and Flying Techniques

19. The take-off of an aircraft should be postponed while there is any risk of flying into the area of an active thunderstorm cell before completing the initial climb. Similarly on arriving in such conditions the approach and landing should, if possible, be delayed or a diversion carried out under advice from ATC.

20. The flight planning should aim at selecting a route and flight level, which will have the least possible traverse in the dangerous parts of thunderstorms.

21. Flying through thunderstorms should be avoided as far as possible. Sometimes, however, it may be necessary to penetrate them. This is always dangerous, but by employing certain techniques it is possible to minimize the risks involved.

22. **Flying Techniques**. The following procedures are recommended for flying through thunderstorm cloud:

a. Select a level below the freezing level (FL) or above 25,000 feet if the aircraft is capable of this. The height band between the freezing level and 25,000 ft is the worst in regard to bumpiness, icing and hail formation.

b. Fasten safety belts and secures any loose articles.

c. Select safe speed for penetration of turbulent zone so that stalling does not occur due to pronounced gusts. For most types of aircraft speeds of penetration of turbulent zones have been laid down.

d. Check all instruments.

e. When within the storm maintain constant heading.

f. Disregard the indications of the ASI. This gives low readings as the pitot tube gets partially blocked due to heavy rain. Radar is one of the best instrumental aids to thunderstorm flying. The area delineated by the radar echo indicates the area of maximum water content which also coincides with maximum turbulence. In the case of line squalls, the best possible course for penetration, or the least active areas can be seen in the radar echo picture. Weather radar pictures on the ground is a good aid not only to the forecaster, but to the aircrew also. When an aircraft is not fitted with an airborne weather radar, aircrew in flight can get while in flight, the latest weather radar report from the nearest Weather Radar Centre.

Benefits of Thunderstorm

23. A thunderstorm is one of the most spectacular weather phenomena in the atmosphere. While it has a number of beneficial effects on human society, still it is dreaded for the intensity and fury of the weather elements associated with some severe thunderstorms. Beneficial effects are:

a. A thunderstorm is a powerful agency for transporting sensible and latent heat from the surface of the earth and injecting it throughout the depth of the troposphere and even adjoining stratosphere.

b. It releases convective instability that gets continuously built up in the tropical atmosphere.

c. Thunderstorms maintain the electrical field of the earth's atmosphere.

d. Thunderstorms fix nitrogen of the atmosphere, converting it into nitrogen compounds that are brought down by rain to the surface of the earth and used by plants as nutrients. Although 80% of the earth's atmosphere is nitrogen gas, nitrogen compounds are rarely present in sufficient quantities in the soil to allow plants to grow at maximum rates. Hence, during recent times, Ammonia (NH_3) fertilizers and other nitrous fertilizers are artificially manufactured and fed into the soil for increased agricultural production. Through lightning and rain nature provides substantial amounts of nitrous compounds that are used directly by plants or indirectly through microbiological organisms that grow with the help of nitrous compounds in the soil and then metabolize atmospheric nitrogen into organic nitrogen compounds. Thunderstorm lightning produces about 30-50% of the nitrous compounds in the atmosphere.

e. In dry regions of the earth, the air in the lower troposphere is so dry that small drops of rain emanating from the base of the cloud would completely evaporate before reaching the ground. Only large drops can survive and give some water to the soil. Thunderstorm is an effective agency to provide such large drops of rain leaving the cloud at its base.

Conclusion

24. Thunderstorm is the combination of both the thunder, a sudden expansion of air around a lightning, and the storm, associated weather like gusty/squally wind, hail etc from a cumulonimbus cloud. Thunderstorms require warm and moist air, as such they frequently occur in the tropics. Severe thunderstorms form in the deep unstable layer of the atmosphere. Triggering action starts the formation of thundercloud. Mainly air mass or heat thunderstorm forms over the tropics while frontal thunderstorms form in the frontal areas in the high latitude. Bangladesh is mainly affected by convective thunderstorms; orographic thunderstorms form in the hilly areas and nocturnal thunderstorms form at night due to radiational cooling.

25. Thunderstorm has got three stages with initial or cumulus stage, mature stage and dissipating stage. The top of the mature stage cloud may reach upto 40,000 feet and duration of mature stage may be about 15-30 minutes. Many flying hazards are accompanied with thunderstorms, like squall, wind shear, microburst, heavy showers, drafts, icing, hail, lightning etc. Not taking-off during thunderstorm is the main flying technique for the aircrew.

MONSOON

Introduction

1. The word Monsoon is derived from the Arabic word MAUSUM, which means SEASON. In meteorology, in brief, Monsoon is nothing but SEASONAL FLOW OF AIR. The essential cause of Seasonal Flow is the differential heating of large land and sea which makes the continents warmer in summer and colder in winter. This results a low pressure system over land in summer and high pressure system in winter. These two alternate pressure systems cause wind to flow in alternate direction, that is, from sea to land in summer and land to sea in winter. It accounts for 75% of the annual rainfall just from June to September.

Aim

2. To impart knowledge on different types of monsoon, onset and withdrawal of monsoon, break monsoon and monsoon depression with associated weather.

Definition

3. In short, monsoon is SEASONAL WIND. Monsoon is defined as a flow of alternate air associated with alternate pressure system having a change of wind direction of at least 120^0 between January and July flow; the mean wind speed should exceed 6 kts at least in one month.

Monsoon Areas

4. Monsoon area is defined as:

a. The prevailing wind shifts by at least 120^0 between January and July.

b. The average frequency of prevailing wind direction in January and July exceeds 40%.

c. The mean resultant winds in at least one month exceed 3 m sec^{-1}.

d. Fewer than one cyclone-anticyclone alternation occurs every two years.

The monsoon area of the world is shown in Figure 01.

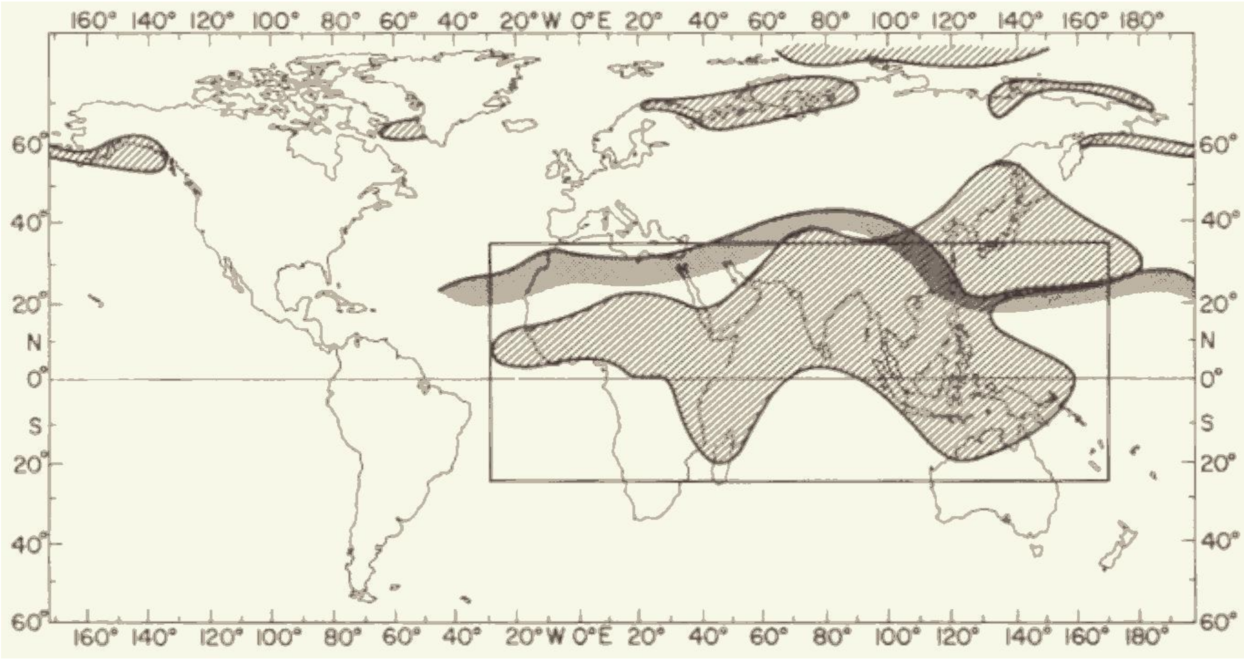


Figure 01: Monsoon area (shadow area) of the world.

Types of Monsoon

5. There are mainly two types of monsoon encountered by Indian sub-continents. They are:

   a. Summer monsoon or SW monsoon.

   b. Winter monsoon or NE monsoon.

6. These two monsoons are separated by two transition periods. They are:

   a. Spring transition or Pre-monsoon.

   b. Autumn transition or Post-monsoon.

Winter Monsoon

7. This monsoon starts setting in the month of December and continues till mid February. In these months the Sun remains in the southern hemisphere and it shines obliquely, and the length of the day is shorter than that of night. As a result, land gets colder than the sea and anti-cyclone builds up over land. During this period low pressure develops over ocean around equatorial area. An intense anti-cyclone forms over Siberia, central pressure 1035 mb, with low pressure 1007 mb over equatorial area. In this period, the south-east Indian peninsula gets its maximum rainfall because of the passage of NE wind over long ocean areas.

Summer Monsoon

8. This monsoon starts setting in the month of May in Andaman Sea and by mid June it extends to whole Bangladesh and India. It remains active till end of August, in exceptional cases till mid September. Heat low develops over NW India and adjoining Pakistan and main high pressure develops over Somalia and adjoining areas. Wind moves from high to low pressure area but due to Coriolis force it deflects to the right after crossing the equator. The deflected wind is then forced to turn left due to the presence of massive Himalayan Hills. As a result, a trough of low forms along the foothills of Himalayas called MONSOON TROUGH. The ONSET and WITHDRAWAL dates of monsoon (SW Monsoon) over Bangladesh and India is shown in Figure 02.

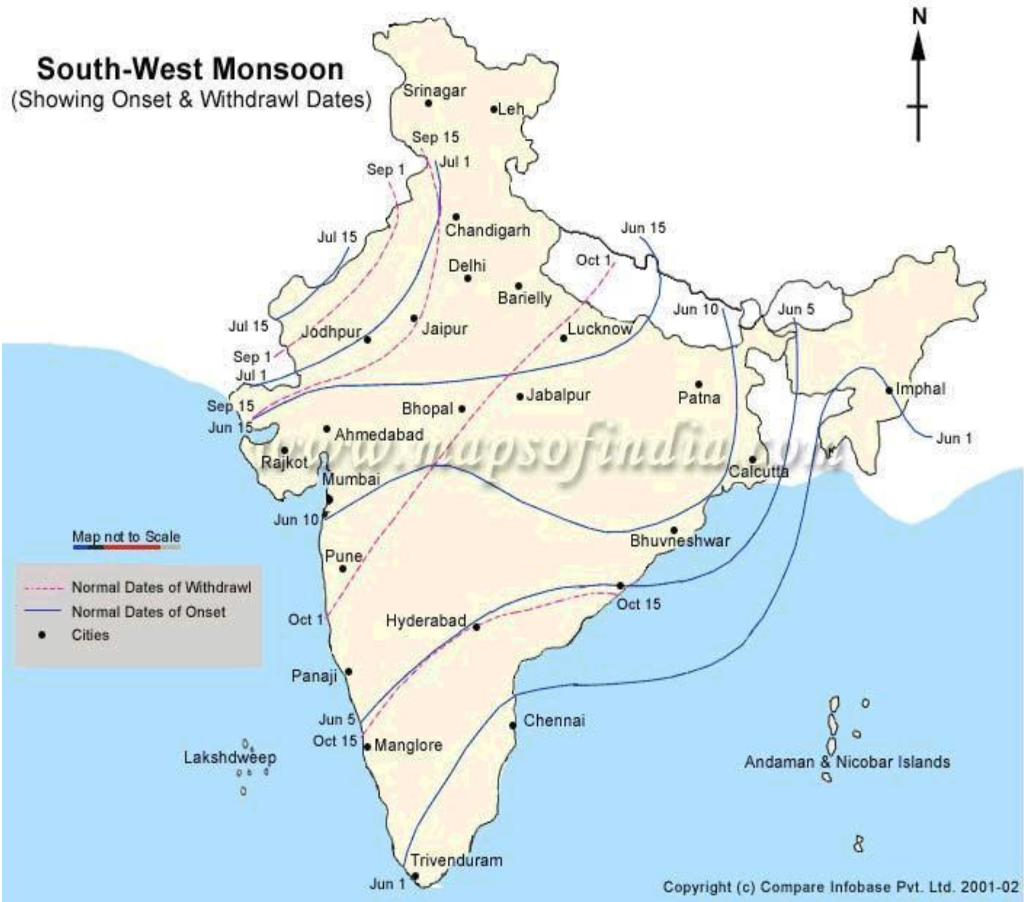


Figure 02: Onset and Withdrawal dates of SW Monsoon over Bangladesh and India.

Onset of SW Monsoon

9. The mean date of onset of SW monsoon in the extreme SE part of the country is 02 June. The SW monsoon first moves to the Meghalaya Plateau, then turns towards the west and reaches the extreme NW part of the country by 15 June. Onset of monsoon is characterized by the successive three days rain with an amount of at least 5 mm each day

and change of wind direction from north to south. The mean date of onset of SW monsoon over Bangladesh is shown in Figure 3.

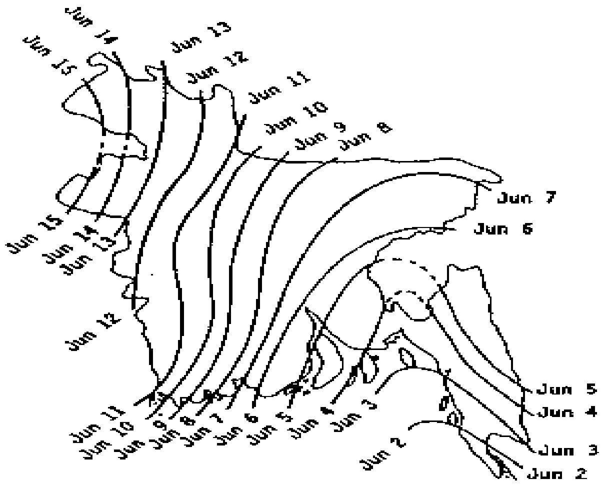


Figure 03: Mean dates of onset of summer Monsoon in Bangladesh.

Withdrawal of SW Monsoon

10. The mean date of withdrawal of summer monsoon is 30 September in the northwestern part and it takes 18 days for the complete withdrawal through the south-eastern part of the country is shown in Figure 2d. The withdrawal is also characterized by the repetitive three days rain and change of wind direction from south to north.

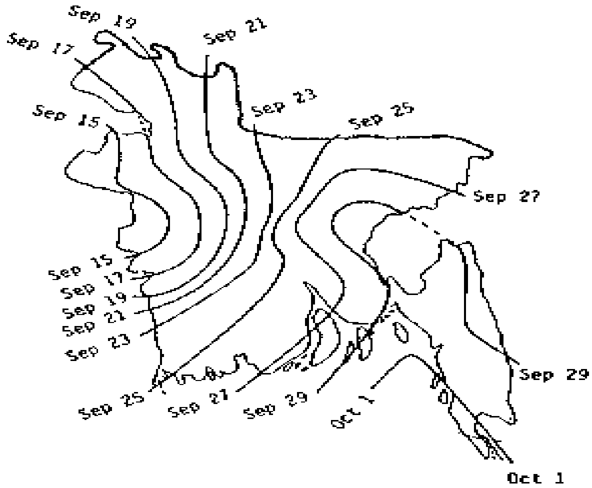


Figure 04: Mean dates of withdrawal of summer monsoon in Bangladesh

Break Monsoon

11. The term Break Monsoon is used to denote the temporary break of rainfall during SW Monsoon. In July and August, there are successive few days, even up to two weeks when rainfall ceases and clouding decreases over India and Bangladesh but increases along Himalayas and part of north-east India and Southern Peninsula.

12. During SW Monsoon period, the axis of the monsoon trough usually lies 450 km off foothills of Himalayas, but it shifts north and come within 200 to 225 km parallel to the Himalayas and pressure of the most parts of the country are above normal. This situation is termed as Break Monsoon. In short, break of rainfall during SW Monsoon is Break Monsoon. Heavy rainfall is experienced over the Himalayas. Heavy rainfall in the catchment's areas causes high flood in Assam, North Bengal and Bihar Rivers. The synoptic pattern in Break Monsoon season is shown in Figure 05.

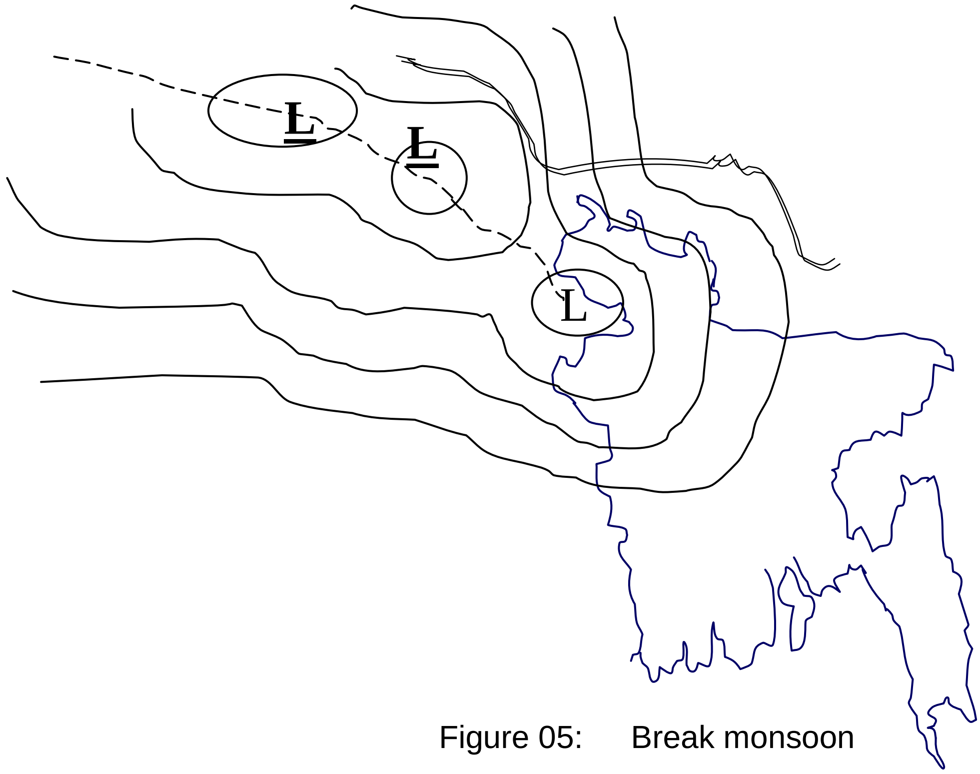


Figure 05: Break monsoon

Monsoon Depression

13. Monsoon depressions are the low pressure areas, with 4 to 6 closed isobars which form over the Bay of Bengal north of 18^0N, move west-northwest at least upto central part of India and give widespread rain the South-west quadrant with very heavy falls, the surface wind, over sea in the depressions is 17 knots to 33 knots and stronger in cyclonic storms. Depressions also form over the Arabian Sea and at times over the land area, which do not affect Bangladesh. The depressions in early June are usually associated with the advance of monsoon.

Different Aspects of Monsoon Depression

14. **Formation**. In June, July and August depressions generally form in the Bay North of 18^0N and West of 92^0E and a few upto 15^0N. In September, however, the formation extends upto 14^0N. Land depressions mostly develop over Northeast India and Bangladesh.

15. **Movement.** In July, depressions move west to northwest over the Bay and cross the country upto 25^0N. They move west-northwards in August. In higher latitudes the movement becomes more northerly. In early June, with advancing monsoon, the depressions may take a north-easterly track and usher the monsoon into Bangladesh, West Bengal, Assam and adjoining states. In September the movement is more or less like June. While the tracks of Bay depressions in July and August are within a narrow belt, they are very much spread in June and September. Movement of Monsoon Depression is shown in Figure 06.

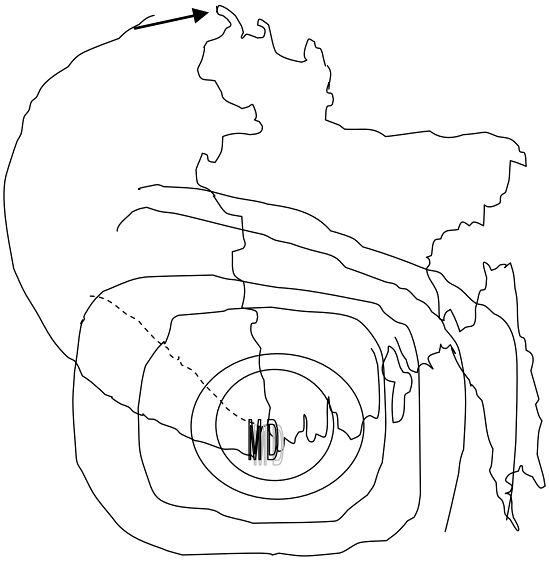


Figure 06: Movement monsoon depression.

16. **Speed of Movement.** Depressions move very slow in the formative stage and speed up as they come over land. In July, the average speed is 5-10 kph to the east of longitude 85^{0}E and 10-20 kph to the west. The speed is faster over central parts of India, may be upto 30 kph. The depressions slow down before they change their track (recurve). In other months speeds are slower. The basic movement of monsoon depression towards west corresponds to upper troposphere easterlies.

17. **Life Period.** The life period of depressions varies from 1 to 9 days, but it is mostly 3-5 days.

18. **Favourable Situations of Formation.** Depressions develop out of the following situation:

a. Development of a diffused low pressure over the North Bay. About 50% of depression is due to intensification of these lows.

b. Appearance of upper air cyclonic circulation at any level upto mid-troposphere and its subsequent settling down to the surface level. This process accounts for 15% cases.

c. About 355% depressions develop out of the diffused lows that travel across Burma into north and adjoining Bay. Some of them are remnants of typhoons.

In addition to these some of the workers associate formation of depression to easterly waves, westerly troughs, upper divergence, strong vertical shear between 850 mb and 200 mb etc.

19. **Further Intensification.** Some of the depressions intensify into cyclonic storms with speed reaching 75 knots. The eye of the storm is of the order of 10-40 km.

20. **Weather.** Study of satellite cloud pictures indicate that most extensive overcast heavy mass of clouds lies in the southern sector. Sometimes it extends to northeast also. Cumuliform clouds are present in the northern sector, which get organised into band as low intensifies into depression. Heavy and steady rains mostly confine to the southwest sector. Elsewhere it is scanty. At the time of recurvature the rain belt shifts to north-northwest. In some cases, particularly in later months, rainfall occurs in all sectors. During formation, a depression may have uniform pattern of rainfall in all sectors. Showery precipitation occurs in the rear of the depression when south or south-westerly winds are strong. The heavy rainfall occurs in a belt of 400 km wide to the left of the track for a length of 500 km from the centre. A second belt of heavy rainfall often develops to the west due to convergence between northwest flows, northeast or east flow around the depression and westerlies to the south. Maximum rainfall in the SW sector has been attributed by various authors to frontal characteristic, convergence, steep pressure gradient, maximum vorticity, maximum curvature of trajectories etc. The MD and weather are shown in Figure 07.

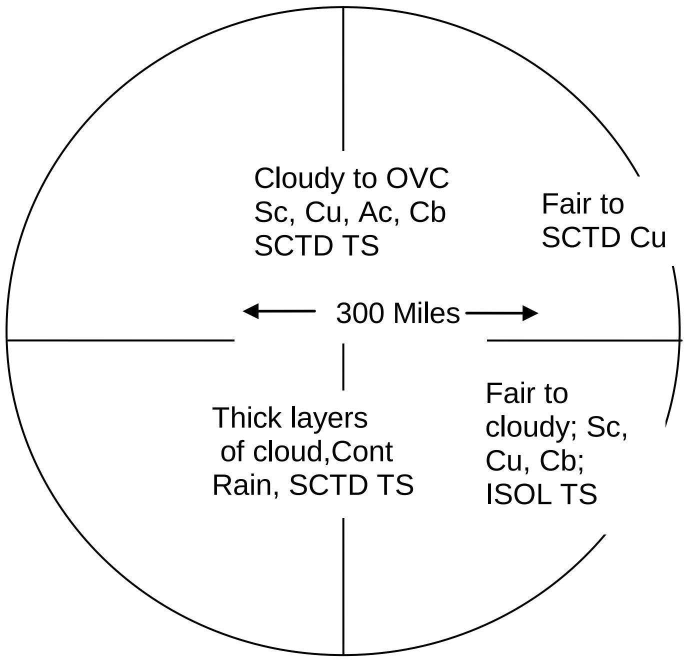


Figure. 07 MD and weather.

21. **Shape of Isobars**. The average number of closed isobars in the monsoon depressions/cyclonic storms is 6. The shape of the isobars is roughly elliptical with elongation in west northwest direction. The pressure gradient is more to the south of the centre.

22. **Upper Air Structure**. The upper air circulation generally extends upto 500 mb and occasionally to 300 mb. The lowest temperature is in the south west quadrant upto 700 mb as fresh air enters and is lifted in this zone of heavy precipitation. Highest temperatures are likely in the NW sector at some distance from centre as the warm air from NW is drawn into the field. The depression centre slopes towards south. The slope is approximately 1 in 40.

Intensity of Monsoon

23. The number of isobars crossing over Bangladesh and Bay of Bengal determines the intensity of monsoon over land and sea. The following table, Table 1, indicates the different intensities of monsoon.

Isobars	Over Land	Over Bay
1-2	Less Active	Weak
3-5	Fairly Active	Moderate
6-8	Active	Strong
≥ 9	Very Active	Vigorous

Table 1 : Intensities of monsoon

Cyclones do not form During Monsoon Period

24. Monsoon depression does not turn into cyclonic storm due to the following reasons:

a. The sensible heat required for a tropical cyclone to be developed cannot be supplied by condensation of water as monsoon trough is confined to the head Bay of Bengal.

b. The presence of strong vertical wind shear over that area at upper level between 850mb and 200 mb.

Conclusion

25. SW monsoon period is the longest hazardous period in Bangladesh. 75% of the total rainfall of the country occurs during this period. Sometimes excess rainfall causes fresh flood all over the country, which causes a great suffering for men and damage for materials. While flying during SW monsoon period, precaution should be taken especially for low clouds, poor visibility and strong surface wind. A little care can save life and properties from destruction.

CLOUDS

Factors Governing Cloud Formation

1. Cloud is formed as a result of condensation of water vapour present in the air. When air is cooled below its dew point the excess water vapour condenses out as visible water droplets. If the condensation occurs near the ground level it takes the form of dew, mist or fog. When condensation occurs above the ground level it takes the form of cloud. Clouds may, therefore, form as a result of cooling of air by one or more of the following processes:

a. Mixing of two masses of nearly saturated air of different temperatures.

b. Cooling by radiation.

c. Adiabatic cooling due to vertical ascent which may be due to :

(1) Orographic uplift.

(2) Convection.

(3) Turbulence.

(4) Frontal Uplift.

Orographic Clouds

2. When the wind is forced upward due to a mountain or hill, it expands and cools, condensation takes place and clouds thus formed are called orographic clouds.

a. **Fohn Effect.** If precipitation occurs on the wind ward side of the barriers, the cloud base on the leeward side becomes higher than on the wind ward side of the barriers, the cloud base on the leeward side becomes higher than on the windward side. The descending air below the cloud base now warms up at the dry adiabatic lapse rate and comes down as a warm dry air.

b. **Types of Cloud**. The type of clouds formed by orographic uplift depends upon the stability or instability of the air mass. If the air is stable St, Cu, Sc clouds will form; if it is unstable Cu or even Cb can form. In this case orography supplies the initial lift only and the amount of instability present.

Turbulence & Convection

3. In the stable air, turbulence causes cooling of the upper level and warming up of the lower level. Water vapour content, which normally decreases with height, becomes uniform throughout the turbulent layer. Thus the air which is carried upward becomes cooler and at the same time damper and sooner or later cloud forms. Since this upward movement covers a large area the cloud takes the form of an extensive sheet. Turbulence is most frequent near the ground level and St or Sc cloud forms. When turbulence occurs in higher levels due to wind shear Ac or Cc clouds form.

4. Convection occurs in an unstable air. When lapse rate exceeds dry adiabatic lapse rate convection takes place. In a saturated mass of air convection takes place when the lapse rate exceeds the saturated adiabatic lapse rate. The requisite lapse rate is most easily established in the lower layers owing to solar heating of the surface. When air of polar origin moves towards lower latitudes it is progressively heated in the lower levels by contact with the warmer surface and thus the lapse rate is increased. The hot parcel of air rises up and cools at the saturated adiabatic lapse rate. Thus convection becomes more vigorous above the condensation level and clouds form up to great heights. Above the condensation level convection will persist if the lapse rate is greater than saturated adidabatic lapse rate. The height upto which cloud will reach depends upon the depth of the layer in which lapse rate exceeding saturated adiabatic lapse rate exists. Where the rising air meets an environment of its own temperature vertical ascent will cease. The clouds of the convection type are Cu or Cb depending upon the depth of the air layer in which lapse rate exceeds saturate adiabatic lapse rate.

Frontal Uplift

5. When two air masses of different temperature and humidity meet, the warm air rises above the colder air along the surface of separation known as the frontal surface. The rising air cools adiabatically, and clouds form when it is cooled below dew point. If the warmer air is stable, stratiform clouds form; and in unstable air connective clouds form. Clouds of the warm front are generally Ci, Cs, As and Ns; clouds of the cold front are Ac, Cu and Cb. As front extends over a wide area these clouds are very extensive.

CLOUDS IN RELATION TO FLYING

	CUMULIFORM	STRATIFORM
Size of water Droplet.	Large	Small
Stability of air	Unstable	Stable
Flying Condition	Rough (Turbulent)	Smooth
Precipitation	Showery	Continuous
Surface Visibility	Good, except in precipitation and blowing snow or dust	Usually poor
Visibility in the air.	10 yards in Cb and Ns.	15 to 200 yards

Simple Classification

6. At first step clouds may be divided into two fundamental classes :

a. **Heap Clouds.** These clouds consist of isolated heaps or towers with marked vertical development. Large isolated clouds are sometimes 30,000 ft. or more in vertical thickness and about the same in horizontal diameter but heap clouds also occur in long narrow belts of almost continuous cloud. Well developed heap clouds are associated with changeable weather, and showers may occur locally, sometimes accompanied by thunderstorms, severe turbulence, and strong vertical currents.

b. **Layer Clouds**. Layer clouds form a fairly level sheet, often covering wide area. The vertical thickness of layers may vary from a few tens of feet to several thousand feet. Such clouds usually give smoother flying conditions & less changeable weather than heap clouds. Since layer clouds are frequently split into filaments or rounded masses a more detailed classification is necessary for general use.

International Classification

7. In this classification clouds are first divided into 3 main families each of which is then subdivided into two or three classes (general) as shown in the accompanying table. The 3 main families consist of high, medium, low clouds. Low clouds also include the clouds of vertical development.

Family	Classes (General)	Abbreviation	Limits of Height within <u>which Cloud Normally Lies</u> Tropical Regions
High Cloud	Circus Cirrostratus Cirrocumulus	Ci Cs Co	20,000 ft to 60,000 ft.
Medium Cloud	Altocumulus Altostratus	Ac As	8,000 ft to 25, 000 ft
Low Cloud	Nimbostratus Stratus Stratocumulus	Ns St Sc	Near surface to 8,000 ft
	Cumulus Cumulonimbus (Clouds of Vertical development)	Cu Cb	Near surface to 60,000 ft

Note: Nimbostratus often extends into medium cloud levels merging with altostratus. The ranges of cloud heights vary considerably with latitudes.

Additional Types of Clouds

8. There are several sub-types and varieties of clouds such as:

a. **Lenticular**. Lenticular clouds have a shape rather like the cross section of a lens. Their position is sometimes related to surface topoghraphy and individual clouds often remain early stationary. Strong vertical currents have occasionally been observed in the vicinity of these clouds.

b. **Castellatus.** As their name implies, castellatus clouds have castellated or turretted appearance. Altocumulus castellatus is usually associated with thundery weather.

c. **Mamma.** The under surface of mamma clouds appears to hange down in fastoons or pouches. Such clouds occasionally appear in very unstable thundery conditions.

d. **Fractus.** Clouds in the form of irregular shreds which have a clearly rugged appearance. This term applied only to stratus and cumulus, eg, stratus fractious.

High Clouds

9. High clouds can be classified into 3 main types.

a. **Cirrus (Ci)**. Detached clouds of delicate and fibrous appearance, without shading, generally white in colour, often of a silky appearance. Cirrus is composed of ice crystals; and it appears in various forms such as isolated tufts, lines drawn across a blue sky, branching feather like plumes, curved lines ending in tufts etc. Cirrus is sometimes arranged in bands.

b. **Cirrostratus (Cs).** A thin whitish veil, which does not blur the outlines of the sun or moon, but gives arise to halos. It is also composed of ice crystals.

c. **Cirrocumulus (Cc).** A cirri form layer or patch composed of small white flakes or of very small globular masses without shadows, which are arranged in groups or lines or more often in ripples resembling those of the shore. Cirrocumulus is generally composed of ice crystals.

Medium Clouds

10. Medium clouds can be classified into 2 main types:

a. **Alto cumulus (Ac).** A layer or patches composed of laminae or rather flattened globular masses, the smallest elements of the regularly arranged layer being thin and small.

b. **Alto stratus (As).** Striated or fibrous well, more or less gray or bluish in colour. The sun or moon may be dimly visible through it but there is no hale phenomena.

Low Clouds

11. Following types of clouds are called low clouds:

a. Low Clouds

(1) Stratus.
(2) Stratocumulus
(3) Nimbostratus

b. Clouds of Vertical Development

(1) Cumulus
(2) Cumulonimbus

Identification of Low Clouds

12. **Stratus (St).** A uniform layer of cloud resembling fog, but not resting on the ground.

13. **Strato cumulus (Sc).** A layer or patches composed or laminae or globular masses; the smallest of the regular arranged elements are fairly large; they are soft and Grey, with darker parts.

14. **Nibo stratus (Ns).** A dense layer of dark Grey colony and nearly uniform appearances and of great vertical thickness; it usually gives precipitation rain, sleet or snow.

Identification of Clouds of Vertical Development

15. **Cumulus (Cu).** Thick clouds with vertical development; the upper surface is dome shaped, and exhibits proturbulance while the base is nearly horizontal.

16. **Cumulo nimbus (Cb).** Heavy masses of cloud, with great vertical development, whose cumuliform summits rise in the form of mountains or towers, the upper part having a fibrous testure and after spreading cut in the shape of an anvil.

TOPIC - 2 : BASIC PRINCIPLES OF FLIGHTS

LIFT AUGMENTATION

Introduction

1. As aircraft have developed over the years so their wing loading has increased from World War I figures of 12 to 15 lb per sq ft to figures in excess of 150 lb per sq ft. These figures are derived from the weight of the aircraft divided by the wing area, which of course, also represents the lift required in level flight per unit area of wing. Now, although aerofoil design has improved, the extra lift required has been produced by flying faster, with the result that where wing loading has gone up by a factor of 10, the stalling speed has also increased by a factor of $\sqrt{10}$. In other words, stalling speeds have increased from about 35 kt to 120 kt. This in turn has led to higher touchdown speeds on landing, and so longer runways and/or special retardation facilities such as tail chutes or arrester wires are needed. The aircraft also has to reach high speeds for unstick. Lift augumentation devices are used to increase the maximum lift coefficient, in order to reduce the air speed at unstick and touchdown.

2. The chief devices used to augment the $C_{\mathbf{Lmax}}$ are:

a. *Slats* - either automatic or controllable by the pilot. Slots are also in this classification.

b. *Flaps* - these include leading edge, trailing edge and jet flaps.

c. Boundary Layer Control (either sucking or blowing air over the wing to re-energize the boundary layer.)

SLATS

Principle of Operation

3. When a small auxiliary aerofoil slat of highly cambered section is fixed to the leading edge of a wing along the complete span and adjusted so that a suitable slot is formed between the two, the C_{Lmax} may be increased by as much as 70%. At the same time, the stalling angle is increased by some 10°. The graph at Fig 1 shows the comparative figures for a slatted and unslatted wing of the same basic dimensions.

4. The effect of the slat is to prolong the lift curve by delaying the stall until a higher angle of attack. When operating at high angles of attack the slat itself is generating a high lift coefficient because of its marked camber. The action of the slat is to flatten the marked peak of the low-pressure envelope at high angles of attack and to change it to one with a more gradual pressure gradient. The flattening of the lift distribution envelope means that the boundary layer does not undergo the sudden thickening that occurred through having to negotiate the very steep gradient that existed immediately behind the former suction peak, and so it retains much of its energy, thus enabling it to penetrate almost the full chord of the wing before separating. Fig 2 shows the alleviating effect of the slat on the low-pressure peak and that, although flatter, the area of the low pressure region, which is proportional to its strength, is unchanged or even increased. The passage of the boundary layer over the wing is assisted by the fact that the air flowing through the slot is accelerated by the venturi effect, thus adding to the kinetic energy of the boundary layer and so helping it to penetrate further against the adverse gradient.

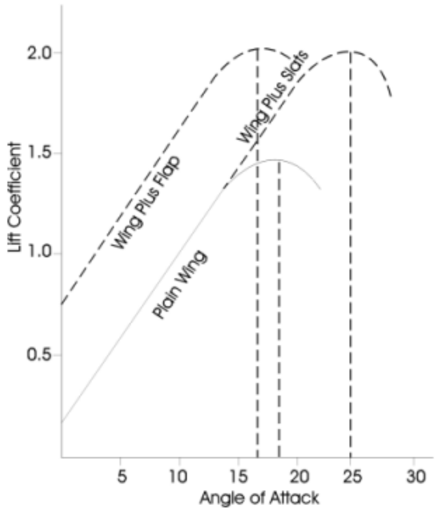


Fig 1 Effect of Flaps and Slats on Lift

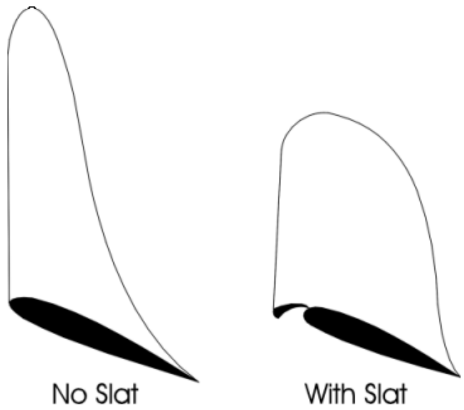


Fig 2 Effect of Slat on the Pressure Distribution

5. As shown in Fig 1, the slat delays separation until an angle of about 25° to 28° is reached, during which time the lift coefficient has risen steadily, finally reaching a peak considerably greater than that of an unslatted wing. Assuming that the C_{Lmax} of the wing is increased by, say 70%, it is evident that the stalling speed at a stated wing loading can be much reduced; for example, if an unslatted wing stalls at a speed of about 100 kt its fully slatted counterpart would stall at about 80 kt. The exact amount of the reduction achieved depends on the length of the leading edge covered by the slat and the chord of the slat. In cases where the slats cover only the wing tips, the increase in C_L is proportionately smaller.

Automatic Slats

6. Since the slat is of use only at high angles of attack, at the normal angles its presence serves only to increase drag. This disadvantage can be overcome by making the slat moveable so that when not in use it lies flush against the leading edge of the wing as shown in Fig 3. In this case the slat is hinged on its supporting arms so that it can move to either the operating position or the closed position at which it gives least drag. This type of slat is fully automatic in that its action needs no separate control.

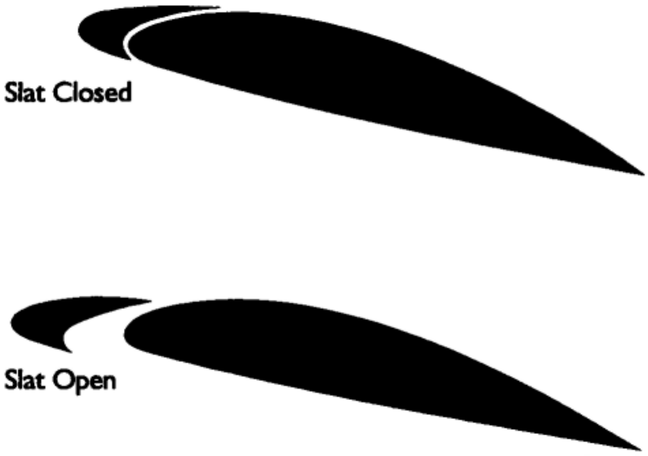


Fig 3 Automatic Slat

7. At high angles of attack the lift of the slat raises it clear of the wing leaving the required slot between the two surfaces which accelerates and re-energizes the airflow over the upper surface.

Uses of the Slat

8. On some high performance aircraft the purpose of slats is not entirely that of augmenting the C_{Lmax} since the high stalling angle of the wing with a full-span slat necessitates an exaggerated and unacceptable landing attitude if the full benefit of the slat is to be obtained. When slats are used on these aircraft, their purpose may be as much to improve control at low speeds by curing any tendencies towards wing tip stalling as it is to augment the lift coefficient.

9. If the slats are small and the drag negligible they may be fixed, ie non-automatic. Large slats are invariably of the automatic type. Slats are often seen on the leading edges of sharply swept-back wings; on these aircraft the slats usually extend along most of the leading edge and besides relieving the tip stalling characteristics they do augment C_L considerably even though the angle of attack may be well below the stalling angle.

10. Automatic slats are designed so that they open fully some time before the speed reaches that used for the approach and landing. During this period they still accomplish their purpose of making the passage of the boundary layer easier by flattening the pressure gradient over the front of the wing. Thus whenever the slat is open, at even moderate angles of attack, the boundary layer can penetrate further aft along the chord thus reducing the thickening effect and delaying separation and resulting in a stronger pressure distribution than that obtained from a wing without slats. As the angle of attack is increased so the effect becomes more pronounced.

11. **Built-In Slots.** Fig 4 shows a variation of the classic arrangement, in which suitably shaped slots are built into the wing tips just behind the leading edge. At higher angles of attack, air from below the wing is guided through the slots and discharged over the upper surfaces, tangential to the wing surface, thereby re-energizing the boundary layer to the consequent benefit of the lift coefficient.

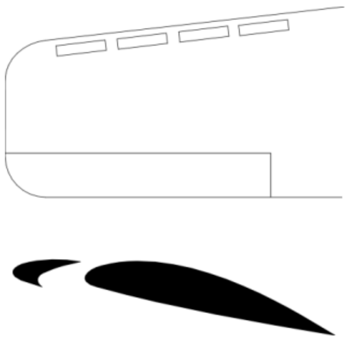


Fig 4 Built-in Slot

12. **Stalling with Slats**. The effect of the slat at the highest angles of attack is to boost the extent of the low-pressure area over the wing. At angles of attack of about 25° the low-pressure envelope has been considerably enlarged and a proportionately larger amount of lift is being developed. When the wing reaches a certain angle the slat can no longer postpone events and the stall occurs. When the powerful low pressure envelope collapses the sudden loss of lift may result in equally sudden changes in the attitude of the aircraft. This applies particularly if one wing stalls before the other; in this case a strong rolling moment or wing dropping motion would be set up.

FLAPS

Purpose

13. The operation of the flap is to vary the camber of the wing section. High lift aerofoils possess a curved mean camber line, (the line equidistant from the upper and lower surfaces); the greater the mean camber the greater the lift capability of the wing. High speed aerofoils however, may have a mean camber line which is straight, and, if either or both the leading edge and trailing edge can be hinged downwards, the effect will be to produce a more highly cambered wing section, with a resultant increase in the lift coefficient.

Action of the Flap

14. Increased camber can be obtained by bringing down the leading or trailing edge of the wing (or both). The use of leading edge flaps is becoming more prevalent on large swept-wing aircraft, and trailing edge flaps are used on practically all aircraft except for the tailless delta. The effect of this increased camber increases the lift, but since the change in camber is abrupt the total increase is not as much as would be obtained from a properly curved mean camber line. (Fig 1 shows the effect of flaps on the C_{Lmax} and stalling angle).

Types of Flap

15. The trailing edge flap has many variations, all of which serve to increase the C_{Lmax}. Some, however, are more efficient than others. Fig 5 illustrates some representative types in use, the more efficient ones are usually more complicated mechanically.

16. The increase in C_{Lmax} obtained by the use of flaps varies from about 50% for the single flap, to 90% for the Fowler type flap. The effectiveness of a flap may be considerably increased if the air is constrained to follow the deflected surface and not to break away or stall. One method of achieving this is by the use of slotted flaps, in which, when the flap is lowered, a gap is made which operates as a slot to re-energize the air in a similar manner to leading edge slots. Some aircraft have double, or even triple-slotted flaps which may give a C_{Lmax} increase of up to 120%.

17. The angle of attack at which the maximum lift coefficient is obtained with the trailing edge flap is slightly less than with the basic aerofoil. Thus, the flap gives an increased lift coefficient without the attendant exaggerated angles made necessary with slats.

Effect of Flap on the Stalling Angle

18. When the trailing edge flap is lowered the angle of attack for level flight under the prevailing conditions is reduced. For each increasing flap angle there is a fixed and lower stalling angle. The lower stalling angle is caused by the change in the aerofoil section when the flap is lowered. Paras 55 to 58 of Chap 7 describe how the use of a trailing edge elevator on a delta wing increases the stalling angle and aircraft attitude at the stall; the same approach can be used to account for the effect of flap on the stalling angle.

High-lift Devices	*Increase of Maximum Lift*	*Angle of basic aerofoil at Maximum Lift*	*Remarks*
 Basic aerofoil		15°	Effects of all high-lift devices depend on shape of basic aerofoil.
 Plain or camber flap	50%	12°	Increase camber. Much drag when fully lowered. Nose-down pitching moment.
 Split flap	60%	14°	Increase camber. Even more drag than plain flap. Nose-down pitching moment.
 Zap flap	90%	13°	Increase camber and wing area. Much drag. Nose-down pitching moment.
 Slotted flap	65%	16°	Control boundary layer. Increase camber. Stalling delayed. Not so much drag.
 Double-slotted flap	70%	18°	Same as single-slotted flap only more so. Treble slots sometimes used.
 Fowler flap	90%	15°	Increase camber and wing area. Best flap for lift. Complicated mechanism. Nose-down pitching moment.

Fig 5 Types of Flaps

19. The trailing edge flap is directly comparable to the trailing edge elevator insofar as the effect on stalling angle is concerned. The raised trailing edge elevator at the stall increases the stalling angle of attack and the aircraft attitude in level flight but the lowered trailing edge flap reduces the stalling angle and the aircraft attitude at the level flight stall. Fig 6 illustrates how the lowered flap affects the angle of attack and the aircraft attitude. Pilots should take care not to confuse attitude with angle of attack, for, as explained in Chap 13, the attitude of the aircraft has no fixed relationship with the angle of attack while manoeuvring.

Changes in Pressure Distribution with Flap

20. All types of flaps, when deployed, change the pressure distribution across the wing. Typical pressure distributions with flap deployed are shown in Fig 7 for plain and slotted flaps. The slotted flap has a much greater intensity of loading on the flap itself.

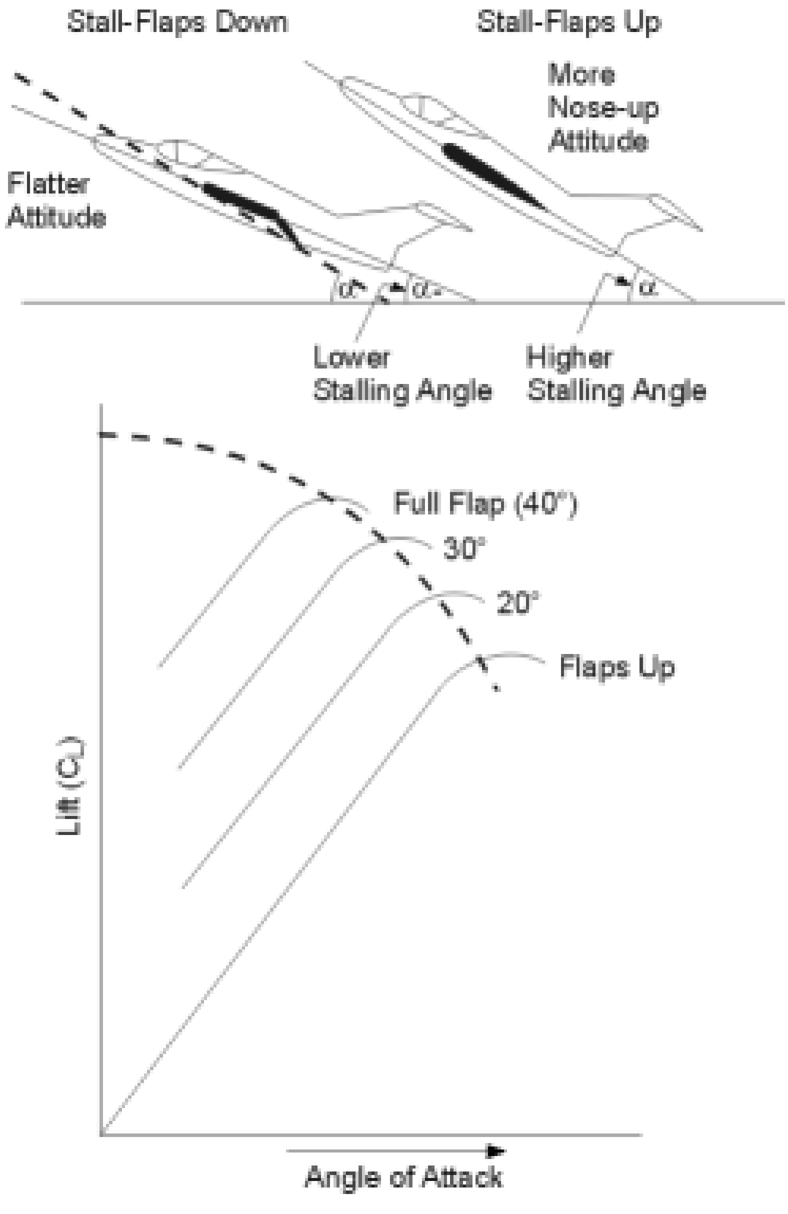


Fig 6 Effect of Flap on Stalling Angle and Level Flight Stalling Attitude

Change in Pitching Moment with Flap

21. All trailing edge flaps produce an increased nose-down pitching moment due to the change in pressure distribution around the wing flap. Flaps, when lowered, may have the added effect of increasing the downwash at the tail. The amount by which the pitching moment is changed resulting from this increase in downwash depends on the size and position of the tail. These two aspects of change in pitching moment generally oppose each other and on whichever aspect is dominant will depend whether the trim change on lowering flap is nose-up or nose-down. Leading edge flaps tend to reduce the nose-down pitching moment and reduce the wing stability near the stall.

Lift/Drag Ratio

22. Although lift is increased by lowering flaps there is also an increase in drag and proportionately the drag increase is much greater when considered at angles of attack about those giving the best lift/drag ratio. This means that lowering flap almost invariably worsens the best lift/drag ratio.

23. For a typical split or trailing edge flap, as soon as the flap starts to lower, the lift and drag start increasing. Assuming that the flap has an angular movement of 90°, for about the first 30° there is a steady rise in the C_L; during the next 30° the C_L continues to increase at a reduced rate and during the final part of the movement a further very small increase occurs.

24. In conjunction with the lift the drag also increases, but the rate of increase during the first 30° is small compared with that which takes place during the remainder of the movement, the final 30° producing a very rapid increase in the rate at which the drag has been rising.

25. When flap is used for take-off or manoeuvring it should be set to the position recommended in the Aircrew Manual. At this setting the lift/drag ratio is such that the maximum advantage is obtained for the minimum drag penalty. For landings, however, the high drag of the fully lowered flap is useful since it permits a steeper approach without the speed becoming excessive (ie it has the effect of an airbrake). The increased lift enables a lower approach speed to be used and the decreased stalling speed means that the touchdown is made at a lower speed. The high drag has another advantage in that it causes a rapid deceleration during the period of float after rounding out and before touching down.

Use of Flap for Take-Off

26. The increased lift coefficient when the flaps are lowered shortens the take-off run provided that the recommended amount of flap is used. The flap angle for take-off is that for the best lift/drag ratio that can be obtained with the flaps in any position other than fully up. If larger amounts of flap are used, although the lift is increased, the higher drag slows the rate of acceleration so that the take-off run, although perhaps shorter than with no flap, is not the shortest possible.

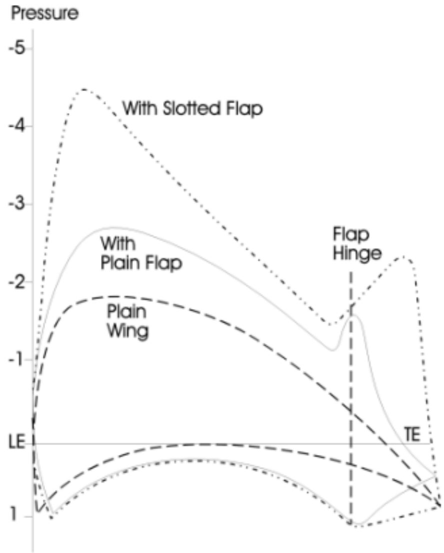


Fig 7 Change in Pressure Distribution with Flaps

27. When the take-off is made at or near the maximum permissible weight, the flaps should invariably be set to the recommended take-off angle so that the maximum lifting effort can be obtained from the wing.

28. **Raising the Flaps in Flight**. Shortly after the take-off, while the aircraft is accelerating and climbing slightly, the action of raising the flaps causes an immediate reduction in the lift coefficient and the aircraft loses height or sinks unless this is countered by an increase in the angle of attack. If the angle of attack is not increased, ie if the pilot makes no correcting movement with the control column, the reduced lift coefficient results in a loss of lift which causes the aircraft to lose height until it has accelerated to a higher air speed that counterbalances the effect of the reduced C_L. When the flaps are raised and the sinking effect is countered by an increased angle of attack, the attitude of the aircraft becomes noticeably more nose-up as the angle of attack is increased. The more efficient the flaps the greater is the associated drop in lift coefficient and the larger the subsequent corrections that are needed to prevent loss of height. On some aircraft it is recommended that the flaps should be raised in stages so as to reduce the C_L gradually and so avoid any marked and possibly exaggerated corrections. This applies sometimes when aircraft are heavily loaded, particularly in the larger types of aircraft.

Leading Edge Flap

29. The effect of leading edge flaps is, as with other flaps, to increase the C_L and lower the stalling speed. However, the fact that it is the leading edge and not the trailing edge that is drooped results in an increase in the stalling angle, and the level flight stalling attitude. The difference is explained as before (Chap 7, para 58, and para 19 of this chapter), by the fact that although the stalling angle measured with respect to the chord line joining the leading and trailing edges of the changed section may not be affected, the stalling angle is increased when measured, as is conventional, with respect to the chord line of the wing with the flap fully raised. Fig 8 illustrates this point. Leading edge flaps are invariably used in conjunction with trailing edge flaps. The operation of the leading edge flap can be controlled directly from the cockpit or it can be linked, for example, with the air speed measuring system so that the flaps droop when the speed falls below a certain minimum and vice versa.

30. The effect of leading edge flaps is similar to that of slats except that the stalling angle is not increased as much. The amount of increase in the C_{Lmax} is about the same in both cases. The leading edge flap is sometimes referred to as a nose flap.

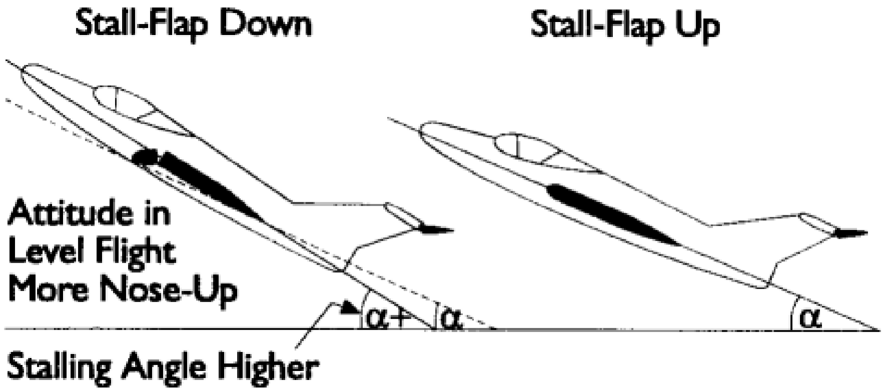


Fig 8 Effect of Leading Edge Flap on Stalling Angle

Jet Flap

31. Jet flap is a natural extension of a slot blowing over trailing edge flaps for boundary layer control, using much higher quantities of air with a view to increasing the effective chord of the flap to produce so-called "super circulations" about the wing.

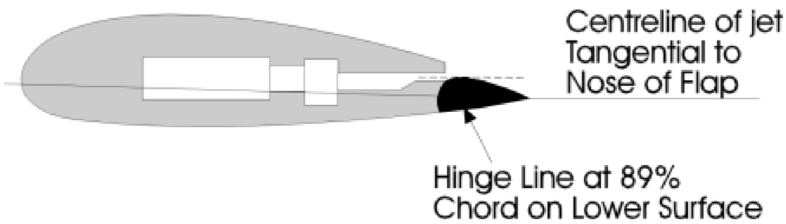


Fig 9 Jet Flap

32. The term jet flap implies that the gas efflux is directed to leave the wing trailing edge as a plane jet at an angle to the main stream so that an asymmetric flow pattern and circulation is generated about the aerofoil in a manner somewhat analogous to a large trailing edge flap. By this means, the lift from the vertical component of the jet momentum is magnified several times by "pressure lift" generated on the wing surface, while the sectional thrust lies between the corresponding horizontal component and the full jet momentum. To facilitate variation of jet angle to the main stream direction, the air is usually ejected from a slot forward of the trailing edge, over a small flap whose angle can be simply varied (see Fig 9). Such basic jet flap schemes essentially require the gas to be ducted through the wing and so are often referred to as "internal flow" systems. Fig 10 illustrates these, and the basics of their ‘external flow’ configurations.

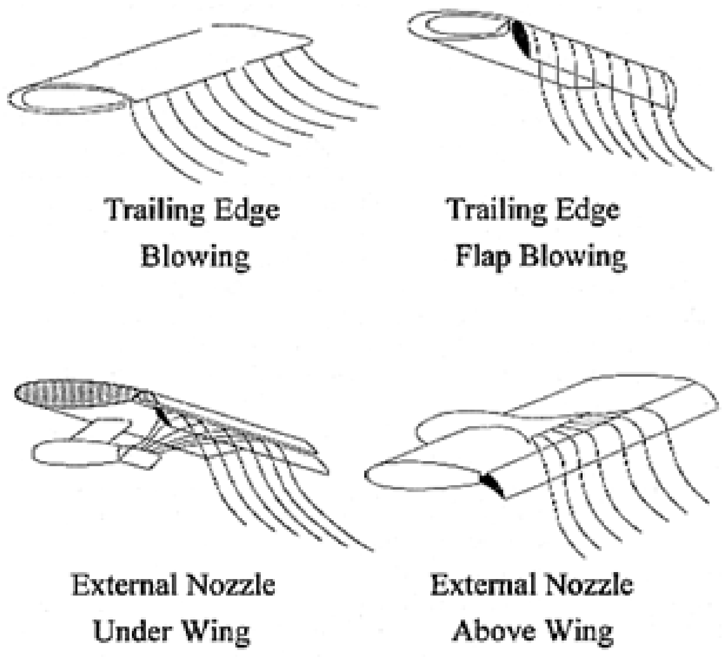


Fig 10 Some Jet Flap Systems

Effect of Sweepback on Flap

33. The use of sweepback will reduce the effectiveness of trailing edge control surfaces and high lift devices. A typical example of this effect is the application of a single slotted flap over the inboard 60% span to both a straight wing and a wing with 35° sweepback. The flap applied to the straight wing produces an increase in the C_{Lmax} of approximately 50%. The same type flap applied to the swept wing produces an increase in C_{Lmax} of approximately 20%. The reason for this is the decrease in frontal area of flap with sweepback.

Effect of Flap on Wing Tip Stalling

34. Lowering flaps may either increase or alleviate any tendency towards the tip stalling of swept wings. When the flaps are lowered the increased downwash over the flaps and behind them induces a balancing upwash over the outer portions of the wing at high angles of attack and this upwash may be sufficient to increase the angle of attack at the tip to the stalling angle. On the other hand, because of the lowered flaps, the higher suctions obtained over the inboard sections of the wing have the effect of restricting the outward flow of the boundary layer and thus a beneficial effect is obtained on wing tip stalling tendencies. The practical outcome of these opposing tendencies is dependent on the pressure configuration.

BOUNDARY LAYER CONTROL

General

35. Any attempt to increase the lifting effectiveness of a given wing directly and fundamentally concerns the boundary layer. If the boundary layer can be made to remain laminar and unseparated as it moves over the wing, then not only is the lift coefficient increased but both surface friction drag and form drag are reduced.

36. There are various methods of controlling the boundary layer so that it remains attached to the aerofoil surface as far as possible. They all depend on the principle of adding kinetic energy to the lower layers of the boundary layer.

Boundary Layer Control by Suction

37. If enough suction could be applied through a series of slots or a porous area on the upper surface of the wing, separation of the boundary layer at almost all angles of attack could be prevented. However, it has been found that the power required to draw off the entire boundary layer so that it is replaced by completely undisturbed air is so large that the entire output of a powerful engine would be required to accomplish this.

38. However, even moderate amounts of suction have a beneficial effect in that the tendency to separate at high angles of attack can be reduced. The effect of moderate suction is to increase the strength and stability of the boundary layer.

39. The effect of the suction is to draw off the lower layer (the sub-layer) of the boundary layer, so that the upper part of the layer moves on to the surface of the wing. The thickness of the boundary layer is thereby reduced and also its speed is increased, since the heavily retarded sub-layer has been replaced by faster moving air.

40. The suction is effected either through a slot or series of slots in the wing surface or by having a porous surface over the area in which suction is required. These devices are positioned at a point where the thickening effect of the adverse gradient is becoming marked and not at the beginning of the adverse gradient. Generally, suction distributed over a porous area has a better effect than the concentrated effect through a slot.

Boundary Layer Control by Blowing

41. When air is ejected at high speed in the same direction as the boundary layer at a suitable point close to the wing surface, the result is to speed up the retarded sub-layer and re-energize the complete boundary layer; again this enables it to penetrate further into the adverse gradient before separating.

42. Very high maximum lift coefficients can be obtained by combining boundary layer control with the use of flaps. In this case the suction, or blowing, of air takes place near the hinge line of the flap. An average C_{Lmax}, for a plain aerofoil is about 1.5, for the same aerofoil with a flap it may be increased to about 2.5; when boundary layer control is applied in the form of blowing or suction over the flap (see Fig 11), the C_{Lmax} may rise to as high as 5. When this figure is put into the lift formula under a given set of conditions it can be seen that the amount of lift obtained is greatly increased when compared with that from the plain aerofoil under the same conditions.

Fig 11 Blown Flap

43. In addition to the use of boundary layer control over the flaps themselves, it can be used simultaneously at the leading edge. In this way even higher lift coefficients can be obtained; the practical limit is set, in the conventional fixed or rotating wing aircraft, by the large amount of power needed to obtain the suction or blowing which is necessary to achieve these high figures. By the use of the maximum amount of boundary layer control, wind tunnel experiments on a full size swept-wing fighter have realized an increase in C_{Lmax} such that the normal 100 kt landing speed was reduced to 60 kt. This is evidence of the importance of the part that the boundary layer plays in aerodynamics.

Vortex Generators

44. Vortex generators can either take the form of metal projections from the wing surface or of small jets of air issuing normal to the surface. Both types work on the same principle of creating vortices which entrain the faster moving air near the top of the boundary layer down into the more stagnant layer near the surface thus transferring momentum which keeps the boundary layer attached further back on the wing. There are many shapes for the metal projections, such as plain rectangular plates or aerofoil sections, the exact selection and positioning of which depends on the detailed particular requirement of the designer. In general, careful design selection can ensure that the increase in lift due to the generators can more than offset the extra drag they cause. An advantage of the air jet type is that they can be switched off for those stages of flight when they are not required and thus avoid the drag penalty.

Deflected Slip-Stream

45. A simple and practical method of using engines to assist the wing in the creation of lift is to arrange the engine/wing layout so that the wing is in the fan or propeller slipstream. This, combined with the use of leading edge slats and slotted extending rear flaps, provides a reliable high lift coefficient solution for STOL aircraft. A more extreme example involves the linking together of engines and synchronization of propellers. The wings and flaps are in the slipstream of the engines and gain effectiveness by deflecting the slipstream downwards.

SUMMARY

Devices to Augment Lift

46. The chief devices used to augment C_{Lmax} are:

a. Slats.

b. Flaps.

c. Boundary layer control.

The effect of the slat is to prolong the lift curve by delaying the stall until a higher angle of attack; the effect of flap is to increase the lift by increasing the camber and the principle of boundary layer control is to add kinetic energy to the sub-layers of the boundary layer.

47. Since the slat is of use only at high angles of attack, at the normal angles its presence serves only to increase drag. This disadvantage is overcome by making the slat movable so that when it is not in use it lies flush against the leading edge of the wing.

48. Flaps may be on the leading or trailing edge and many aircraft have them on both. Besides increasing the camber of the wing, many types of flap also increase the wing area. Trailing edge flaps reduce the stalling angle; leading edge flaps increase the stalling angle.

49. The main methods of boundary layer control are:

a. Blowing.

b. Sucking.

c. Vortex generators.

FLIGHT CONTROLS

General Considerations

1. All aircraft have to be fitted with a control system that will enable the pilot to manoeuvre and trim the aircraft in flight about each of its three axes.

2. The aerodynamic moments required to rotate the aircraft about each of these axes are usually produced by means of flap-type control surfaces positioned at the extremities of the aircraft so that they have the longest possible moment arm about the CG.

3. There are usually three separate control systems and three sets of control surfaces, namely:

   a. Rudder for control in yaw.

   b. Elevator for control in pitch.

   c. Ailerons for control in roll (the use of spoilers for control in roll is also discussed in this chapter).

4. On some aircraft the effect of two of these controls is combined in a single set of control surfaces; for example:

   a. Elevons. Combine the effects of ailerons and elevators.

   b. Ruddervator. ie Vee or butterfly tail, combining the effects of rudder and elevators.

   c. Tailerons. Slab tail surfaces that move either together, as pitch control, or independently for control in roll.

5. It is desirable that each set of control surfaces should produce a moment only about the corresponding axis. In practice, however, moments are often produced about the other axes as well, eg adverse yaw due to aileron deflection. Some of the design methods used to compensate for these cross-effects are discussed in later paragraphs.

Control Characteristics

6. **Control Power and Effectiveness.** The main function of a control is to allow the aircraft to fulfill its particular role. This aspect is decided mainly by:

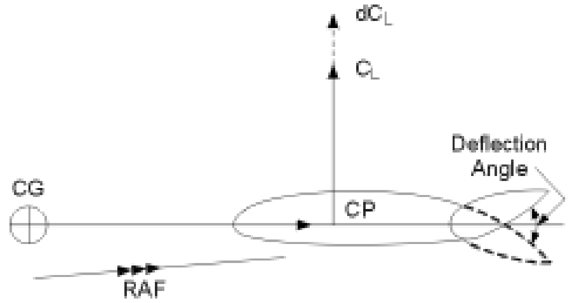
   a. Size and shape of the control.

   b. Deflection angle.

   c. EAS^2

   d. Moment arm (distance from CG).

In practice the size and shape of the control surface are fixed and, since the CG movement is small, the moment arm is virtually constant. The only variables in control effectiveness are speed and effective deflection angle.



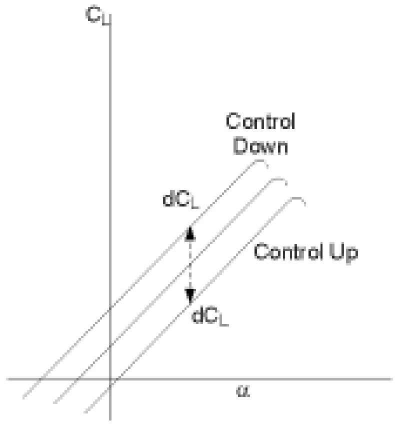


Fig 1 Effect of Elevator Deflection on the Lift Coefficient Curve

7. **<u>Control Moment</u>.** Consider the effect of deflecting an elevator downwards, the angle of attack and the camber of the tailplane are both increased, thereby increasing the C_L value. The moment produced by the tail is the product of the change in lift (tail) x the moment arm to the CG (see Fig 1).

8. **<u>Effect of Speed</u>**. The aerodynamic forces produced on an aerofoil vary as the square of the speed (see Chap 2); it follows then, that for any given control deflection, the lift increment - and so the moment - will vary as the square of the speed, EAS^2. The deflection angle required to give an attitude change, or response, is inversely proportional to the EAS^2. To the pilot this means that when the speed is reduced by half, the control deflection is increased fourfold to achieve the same result. This is one of the symptoms of the level flight stall, erroneously referred to as ‘sloppy controls’.

9. **<u>Control Forces</u>.** When a control surface is deflected, eg down elevator, the aerodynamic force produced by the control itself opposes the downwards motion. A moment is thus produced about the control hinge line, and this must be overcome in order to maintain the position of the control. The stick force experienced by the pilot depends upon the hinge moment and the mechanical linkage between the stick and the control surface. The ratio of stick movement to control deflection is known as the stick-gearing, and is usually arranged so as to reduce the hinge moment.

Aerodynamic Balance

10. If control surfaces are hinged at their leading edge and allowed to trail from this position in flight, the forces required to change the angle on all except light and slow aircraft would be prohibitive. To assist the pilot to move the controls in the absence of powered or power-assisted controls, some degree of aerodynamic balance is required.

11. In all its forms, aerodynamic balance is a means of reducing the hinge moment and thereby reducing the physical effort experienced in controlling an aircraft. The most common forms of aerodynamic balance are:

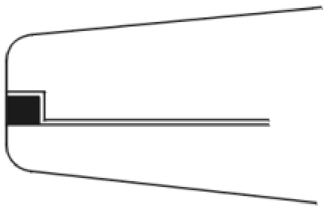
a. Horn balance.

b. Inset hinge.

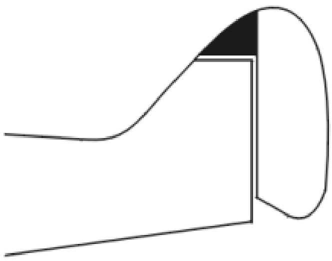
c. Internal balance.

d. Various types of tab balance.

12. **<u>Horn Balance</u>.** On most control surfaces, especially rudders and elevators, the area ahead of the hinge is concentrated on one part of the surface in the form of a horn (see Fig 2). The horn thus produces a balancing moment ahead of the hinge-line. In its effect the horn balance is similar to the inset hinge.



a Shielded Horn



b Unshielded Horn

Fig 2 Horn Balance

13. **<u>Inset Hinge</u>**. The most obvious way to reduce the hinge moment (see Fig 3a) is to set the hinge-line inside the control surface thus reducing the moment arm. The amount of inset is usually limited to 20-25% of the chord length, this ensures that the CP of the control will not move in front of the hinge at large angles of control deflection (see Fig 3b).

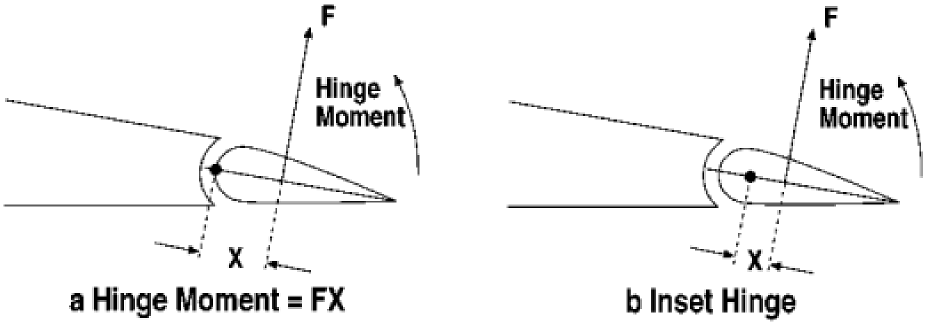


Fig 3 Hinge Moment and Inset Hinge

14. **<u>Over Balance</u>.** Should the control CP move ahead of the hinge line, the hinge moment would assist the movement of the control and the control would then be over-balanced.

15. **<u>Internal Balance</u>.** Although fairly common in use, this form of aerodynamic balance is not very obvious because it is contained within the contour of the control. When the control is moved there will be a pressure difference between upper and lower surfaces. This difference will try to deflect the beak ahead of the hinge-line on the control producing a partial balancing moment. The effectiveness is controlled in some cases by venting air pressure above and below the beak, see Fig 4.

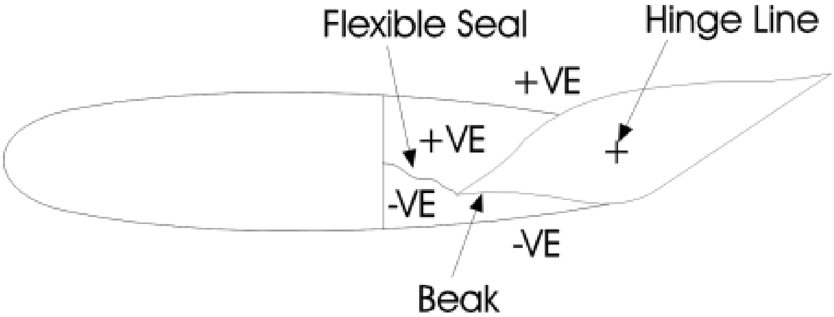


Fig 4 Internal Balance

16. **<u>Tab Balance</u>.** This subject is fully covered in Chap 10, Trimming and Balance Tabs.

<u>Mass Balance - Flutter</u>

17. **<u>Torsional Aileron Flutter</u>**. This is caused by the wing twisting under loads imposed on it by the movement of the aileron. Fig 5 shows the sequence for a half cycle, which is described as follows:

a. The aileron is displaced slightly downwards, exerting an increased lifting force on the aileron hinge.

b. The wing twists about the torsional axis-the trailing edge rising, taking the aileron up with it. The CG of the aileron is behind the hinge line; its inertia tends to make it lag behind, increasing aileron lift, and so increasing the twisting moment.

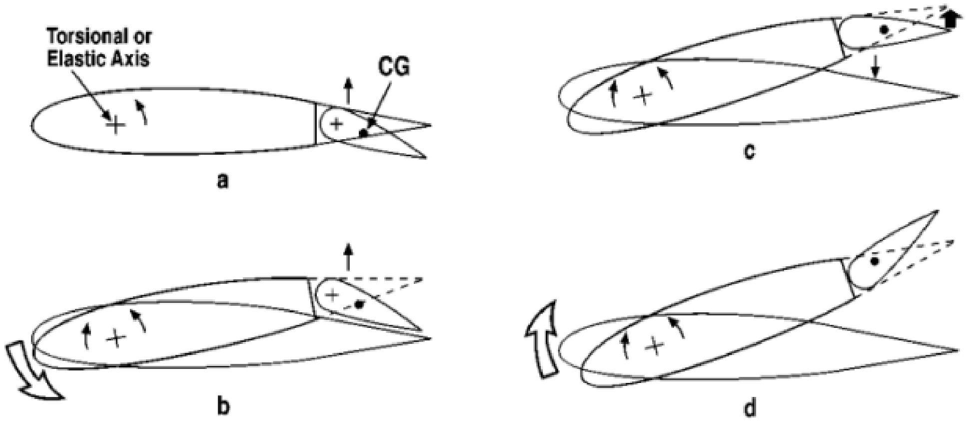


Fig 5 Torsional Aileron Flutter

c. The torsional reaction of the wing has arrested the twisting motion but the air loads on the aileron, the stretch of its control circuit, and its upward momentum, cause it to overshoot the neutral position, placing a down load on the trailing edge of the wing.

d. The energy stored in the twisted wing and the reversed aerodynamic load of the aileron cause the wing to twist in the opposite direction. The cycle is then repeated. Torsional aileron flutter can be prevented either by mass-balancing the ailerons so that their CG is on, or slightly ahead of, the hinge line, or by making the controls irreversible. Both methods are employed in modern aircraft; those aircraft with fully powered controls and no manual reversion do not require mass-balancing; all other aircraft have their control surfaces mass-balanced.

18. **Flexural Aileron Flutter**. Flexural aileron flutter is generally similar to torsional aileron flutter, but is caused by the movement of the aileron lagging behind the rise and fall of the outer portion of the wings as it flexes, thus tending to increase the oscillation. This type of flutter is prevented by mass-balancing the aileron. The positioning of the mass-balance weight is important - the nearer the wing tip the smaller the weight required. On many aircraft the weight is distributed along the whole length of the aileron in the form of a leading edge spar, thus increasing the stiffness of the aileron and preventing a concentrated weight starting torsional vibrations in the aileron itself.

19. **Other Control Surfaces**. So far only wing flutter has been discussed, but a few moments consideration will show that mass-balancing must be applied to elevators and rudders to prevent their inertia and the springiness of the fuselage starting similar troubles. Mass-balancing is extremely critical; hence to avoid upsetting it, the painting of aircraft markings etc is no longer allowed on any control surface. The danger of all forms of flutter is that the extent of each successive vibration is greater than its predecessor, so that in a second or two the structure may be bent beyond its elastic limit and fail.

Control Requirements

20. The main considerations are outlined briefly below:

a. **Control Forces**. If the stick forces are too light the pilot may overstress the aircraft, whereas if they are too heavy he will be unable to manoeuvre it. The effort required must be related to the role of the aircraft and the flight envelope.

b. **Control Movements**. If the control movements are too small the controls will be too sensitive, whereas if they are too large the designer will have difficulty in fitting them into the restricted space of the cockpit.

c. **Control Harmony**. An important factor in the pilot's assessment of the overall handling characteristics of an aircraft is the "harmony" of the controls with respect to each other. Since this factor is very subjective it is not possible to lay down precise quantitative requirements. One method often used is to arrange for the aileron, elevator and rudder forces to be in the ratio 1:2:4.

Control Response

21. **Ailerons**. Consider the effect of applying aileron. Deflection of the controls produces a rolling moment about the longitudinal axis and this moment is opposed by the aerodynamic damping in roll (the angle of attack of the down-going wing is increased while that of the up-going wing is decreased, see Chap 14). The greater the rate of roll, the greater the damping. Eventually the rolling moment produced by the ailerons will be exactly balanced by the damping moment and the aircraft will attain a steady rate of roll. Usually the time taken to achieve the 'steady state' is very short, probably less than one second. Thus, over most of the time that the ailerons are being used, they are giving a steady rate of roll response and this is known as steady state response. The transient response is that which is experienced during the initiation period leading to a steady manoeuvre.

22. **Rate versus Acceleration Control**. A conventionally-operated aileron is therefore described as a rate control, that is the aircraft responds at a steady rate of movement for almost all of the time. The stick force required to initiate a manoeuvre may be less than, or greater than, the stick force required to sustain the manoeuvre, eg rolling. A favourable response is usually assumed to be when the initiation force is slightly greater than the steady force required, the difference being up to 10%. On some modern aircraft the transient response time to aileron deflection is increased. By the time the steady rate of roll is obtained the aileron is being taken off again. In these circumstances the aileron control is producing a rate of roll response which is always increasing and it is then described as an acceleration control.

23. **Elevators**. When the elevators are used they produce a pitching moment about the lateral axis. The resulting pitching movement is opposed by the aerodynamic damping in pitch and by the longitudinal stability of the aircraft (see Chap 14). The response to the elevator is a steady state change in angle of attack with no transient time, that is a steady change of attitude. Elevators are therefore described as a displacement control.

24. **Rudders**. The yawing moment produced by rudder deflection is opposed by aerodynamic damping in yaw and by the direction of the aircraft. The response to the rudder is a steady state of change of angle of attack on the keel surfaces of the aircraft, with no transient time. The rudder control has a similar response to the elevator and is therefore also described as a displacement control.

Steady State Response

25. In Chap 14 (Stability) it is shown that stability opposes manoeuvre; more precisely, the steady state response to control deflection is greatly affected by the static stability. This is easily seen when considering the response to rudder; the heavy rudder force required to sustain a steady yawing movement is a result of the strong directional static stability of most aircraft.

26. The steady state response to controls is of greater importance to the pilot and this subject is discussed in the following paragraphs.

PRIMARY CONTROL SURFACES

Elevators

27. The elevators are hinged to the rear spar of the tailplane and are connected to the control column so that forward movement of the column moves the elevator downwards and backward movement moves the elevator upwards. When the control column is moved back and the elevator rises, the effect is to change the overall tailplane/elevator section to an inverted aerofoil which supplies a downward force on the tail of the aircraft and, as seen by the pilot, raises the nose. The opposite occurs when a forward movement is made.

28. Elevators are normally free from undesirable characteristics, but large stick forces may be experienced on some aircraft if the aerodynamic balance of the elevators or the stability characteristics of the aircraft are at fault. The tail moment arm is determined by the position of CG, and to retain satisfactory handling characteristics throughout the speed range, the CG position must be kept within a certain limited range. If the CG moves too far forward, the aircraft becomes excessively stable and the pilot will run out of up-elevator before reaching the lowest speeds required.

29. Consider an aircraft in the round-out and landing where longitudinal static stability opposes the nose-up pitch. The downwash angle at the tail is much reduced by the ground effect thereby increasing the effective angle of attack at the tail. This results in a reduced tail-down moment in pitch, therefore a greater elevator deflection angle is required to achieve the landing attitude than would be required to achieve the same attitude at height. A forward movement of the CG would add to this problem by increasing the longitudinal stability.

30. Some tailless delta aircraft require a movement aft of the CG (fuel transfer) to ensure that the elevator movement is sufficient to achieve the landing attitude.

31. Some light aircraft, notably civilian flying club types with a tricycle undercarriage have undersized elevators in order to make the aircraft ‘unstallable’.

Ailerons

32. It has been seen that the aileron is a rate control and the rate of roll builds up rapidly to a steady value dictated by the damping in roll effect. The value of the steady rate of roll produced by a given aileron deflection will depend upon the speed and altitude at which the aircraft is flying. Additional effects due to aero-elasticity and compressibility may be present and will modify the roll response.

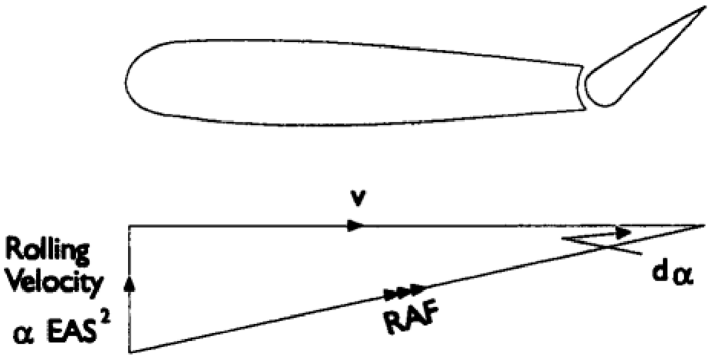


Fig 6 Damping in Roll Effect - Downgoing Wing

33. **Effect of Altitude**. In a steady state of roll the rolling force and the damping in roll force are balanced. The rolling force is caused by the change in lift due to aileron deflection and is proportional to the amount of aileron deflection and to EAS. The damping force is due to the change in lift caused by the increase in angle of attack of the downgoing wing and the decrease in angle of attack of the upgoing wing. The value of the damping angle of attack can be found by the vector addition of the TAS and the rolling velocity as illustrated in Fig 6. It can be seen that for a constant damping angle of attack the rolling force, and therefore rate of roll, will increase in direct proportion to TAS. When an aircraft is climbed at a constant EAS the rate of roll for a given aileron deflection therefore increases because TAS increases with altitude.

34. **Effect of Forward Speed.** It has been shown that the rolling force is proportional to the amount of aileron deflection and to EAS. It follows that rate of roll increases in proportion to EAS.

35. **Aero-elastic Distortion**. Ailerons are located towards the wing tips by the necessity in most aircraft to utilize trailing edge flaps for landing and take-off. This may cause the wing to twist when the ailerons are deflected and lead to an effect known as “aileron reversal”. It must be recognized that aero-elastic distortion of the airframe may affect stability and control in pitch and yaw as well as in roll. Because the wings are usually the least rigid part of the airframe however, aileron reversal is important and reduces the ultimate rate of roll available at high forward speeds.

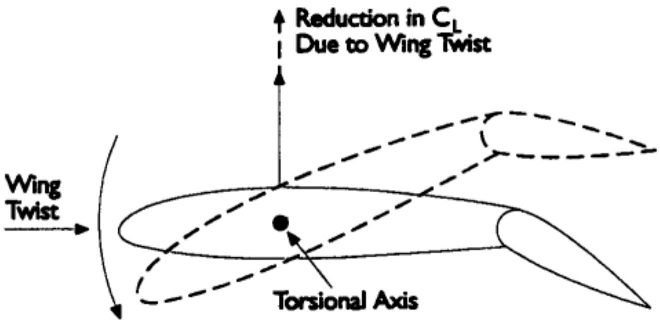


Fig 7 Aero-elastic Distortion

36. In Fig 7 it can be seen that deflection of the aileron down produces a twisting moment about the torsional axis of the wing. The torsional rigidity of the wing depends on the wing structure but will normally be strong enough to prevent any distortion at low speeds. Aileron power, however, increases as the square of the forward speed, whereas the torsional stiffness in the wing structure is constant with speed. At high speeds therefore, the twisting moment due to aileron deflection overcomes the torsional rigidity of the wing and produces a change in incidence which reduces the rate of roll. On the rising wing illustrated in Fig 7 the incidence is reduced whereas on the down going wing the effect is to increase the incidence. A flight speed may be reached where the increment of C_L produced by deflecting aileron is completely nullified by the wing twisting in the opposite sense. At this speed, called reversal speed, the lift from each wing is the same in spite of aileron deflection, and the rate of roll will be zero. At still higher speeds the direction of roll will be opposite to that applied by the pilot. Reversal speed is normally outside the flight envelope of the aircraft but the effects of aero-elastic distortion may be apparent as a reduction in roll rate at the higher forward speeds.

37. **<u>Aileron Response at Low Speeds</u>**. Deflecting an aileron down produces an effective increase in camber and a small reduction in the critical angle of attack of that part of the wing to which the aileron is attached (usually the wing tip). It is therefore important that the wings should stall progressively from root to tip in order to retain aileron effectiveness at the stall. Rectangular straight wings are not much of a problem because washout is usually incorporated to reduce vortex drag. Swept wings, however, are particularly prone to tip stall and design features may have to be incorporated to retain lateral control at low speeds. Loss of effectiveness of the down-going aileron due to tip stall will not necessarily result in a reversal in the direction of roll (ie wing-drop). The up-going aileron will usually retain its effectiveness and produce a lesser but conventional response. The factor which has the most significant effect on aircraft response at high a is the damping in roll effect. It has been seen that when the aircraft is rolling, the angle of attack of the down-going wing is increased while that of the rising wing is decreased. If the aircraft is close to the stall the damping effect is reversed and the change in the rolling moments assists the rotation, see Fig 8. This leads to the phenomenon known as autorotation.

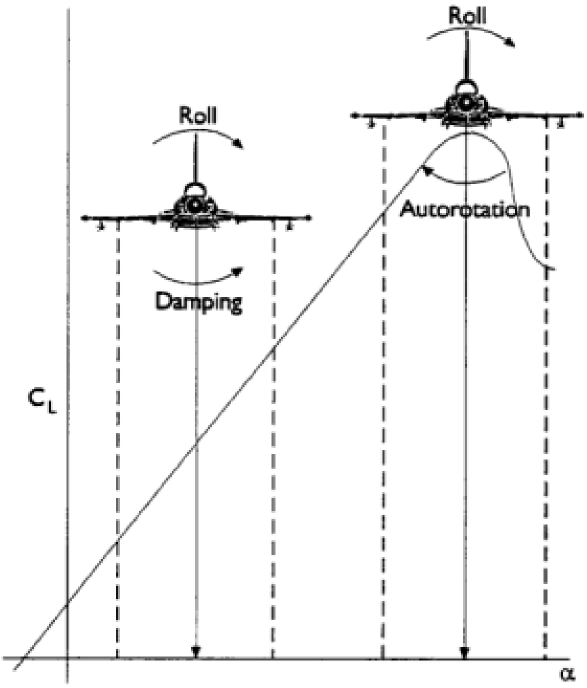


Fig 8 Damping in Roll

38. **Adverse Aileron Yaw.** Unless they are carefully designed aerodynamically, the ailerons will materially alter the drag force on the wing in addition to the desired change in lift force. When an aileron is deflected downwards both the vortex drag and the boundary layer drag are increased. On the aileron-up wing, however, the vortex drag is decreased, though the boundary layer drag may be still increased. The changes in the drag forces are such as to produce a yawing moment causing the aircraft to yaw in the opposite sense to the applied roll. Adverse yaw is produced whenever the ailerons are deflected but the effect is usually reduced by incorporating one or more of the following design features:

a. **Differential Ailerons**. For a given stick deflection the up-going aileron is deflected through a larger angle than the down-going aileron thus reducing the difference in drag and the adverse yaw.

b. **Frise-Type Ailerons**. The nose of the upgoing aileron protrudes into the airstream below the wing to increase the drag on the down-going wing. This arrangement has the additional advantage that it assists the aerodynamic balancing of the ailerons.

c. **Coupling of Controls**. A method used in some modern aircraft to overcome the adverse yaw is to gear the rudder to the ailerons so that when the ailerons are deflected the rudder moves to produce an appropriate yawing moment.

d. **Spoilers.** On some aircraft, spoilers in the form of flat plates at right angles to the airflow are used to increase the drag of the down-going wing. Spoilers are sometimes the only form of lateral control used at high speeds (eg the ailerons are used at low speeds, where spoilers are least effective, but spoilers alone at high speeds). Other uses of spoilers are as airbrakes, when the spoilers of both wings operate together, or as lift dumpers, when the aircraft has landed. They are usually hydraulically operated.

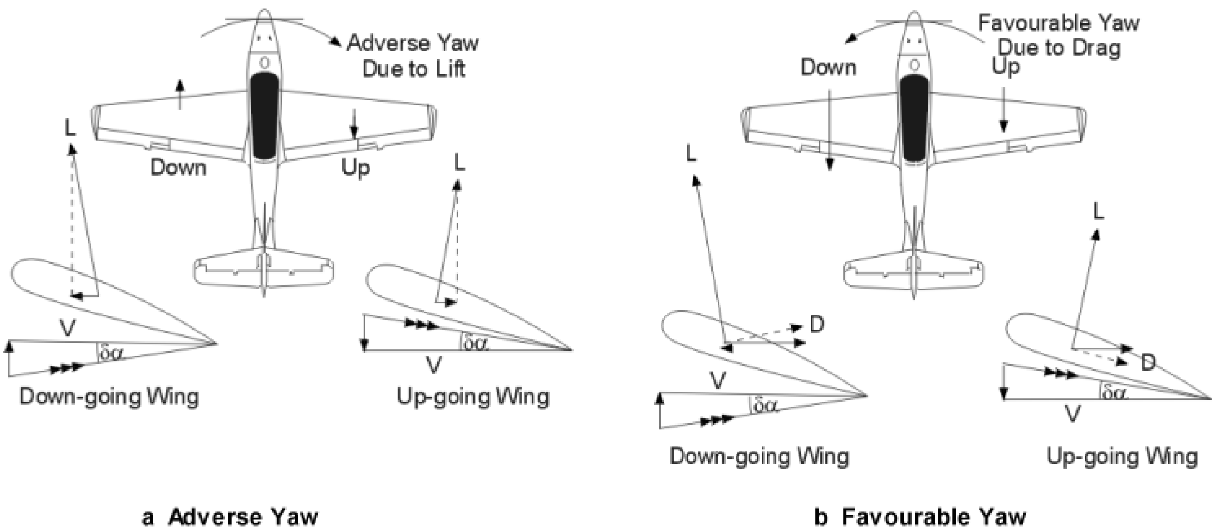


Fig 9 Cross-Coupling Response

39. **Cross-Coupling Response**. When an aircraft is rolling the increased angle of attack of the down-going wing increases both the lift and the drag, whereas on the up-going wing the lift and drag are reduced. The lift and drag forces are by definition, however, perpendicular and parallel respectively to the local relative airflow on each wing. The projections of the lift forces onto the yawing plane produce a yawing moment towards the rising wing (ie an adverse yaw) as shown in Fig 9a. This is partially offset by the projections of the drag forces onto the yawing plane which usually produce a yaw in the same direction as roll, Fig 9b. For a given rate of roll the change in angle of attack will be greatest at low forward speeds. The adverse yaw due to roll is therefore greatest at low speed and may eventually become favourable at some high forward speed.

40. **Response to Sideslip**. The lateral response of the aircraft to sideslip is usually called the 'dihedral effect' and produces a rolling moment opposite to the direction of sideslip. In most conventional aircraft this contribution is dominated by the yaw due to sideslip.

41. **Overbalance**. This may occur at any airspeed on some aircraft not fitted with power-operated controls, but usually only at the larger control angles. It is shown by a progressive decrease, instead of an increase, of the aileron stick force as the control column is moved, ie a tendency for the ailerons to move to their full travel of their own accord. In some cases this may happen fairly suddenly.

42. *Snatch*. Snatching usually occurs at or near the stall, or at high Mach numbers. It is caused by a continuous and rapid shifting of the centre of pressure of the aileron due to the disruption of the airflow over the surface, resulting in a snatching or jerking of the control, which may be violent.

The Rudder

43. The rudder, which is hinged to the rear of the fin, is connected to the rudder bar. Pushing the right pedal will cause the rudder to move to the right, and in so doing alter the aerofoil section of the fin/rudder combination. This provides an aerodynamic force on the rear of the aircraft which will move it to the left or, as the pilot sees it, the nose will yaw to starboard. Rudder effectiveness increases with speed; whereas a large deflection may be required at low speed to yaw a given amount, a much smaller deflection is needed at the highest speeds. The steady response of an aircraft to rudder deflection is complicated by the fact that yaw results in roll, and rudder deflection may also cause the aircraft to roll.

44. **Damping in Yaw**. Just as there is damping in pitch and roll, so also is the aircraft damped in yaw. The effect is similar in principle to damping in roll, in that the yawing velocity produces a change in the angle of attack of the keel surfaces. Keel surface moments fore and aft of the CG oppose the yawing movement, and these moments exist only while the aircraft is yawing. For simplicity, Fig 10 shows the damping effect on the fin and rudder. The wings also produce a small damping in yaw effect because the outer wing moves faster than the inner wing and therefore produces more drag. The damping in yaw effect decreases with altitude for the reasons stated in para 33.

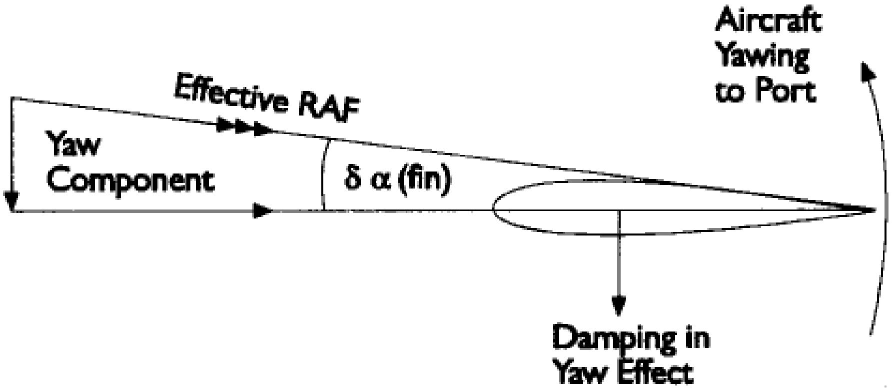


Fig 10 Damping in Yaw

45. **Roll Due to Rudder Deflection**. The rudder control inevitably produces a rolling moment because the resultant control force acts above the longitudinal axis of the aircraft. Usually this effect is small but on aircraft with a tall fin and rudder it can be important and is sometimes eliminated by linking up the rudder and aileron circuits.

46. **Cross-Coupling Response**. The response of the aircraft in roll to rudder deflection arises from the resulting yawing motion and/or sideslip. The roll due to sideslip, ie the dihedral effect, has a powerful cross-coupling effect, particularly on swept-wing aircraft. Rudder control is often used to pick up a dropped wing at low speeds in preference to using large aileron deflection. If the starboard wing drops and port rudder is applied, the aircraft sideslips to starboard and the dihedral effect produces a rolling moment tending to raise the lower wing. The roll due to yaw (ie rate of yaw) arises because the outer wing moves faster than the inner wing and therefore produces more lift. The roll with yaw is greatest at high angles of attack/low speeds.

47. **Rudder Overbalance**. A fault which may be encountered is overbalance. This is indicated by a progressive lessening of the foot loads with increasing rudder displacement. If, owing to a weakness in design, the aerodynamic balance is too great, it will become increasingly effective as the rudder is moved and may eventually cause it to lock hard over when the centre of pressure moves in front of the hinge-line. At large angles of yaw (sideslip) the fin may stall causing a sudden deterioration in rudder control and directional stability and, at the same time, rudder overbalance. If this is encountered the yaw must be reduced by banking in the direction in which the aircraft is yawing and not by stabilizing the yaw by instinctively applying opposite bank. The correct action reduces the sideslip by converting the motion into a turn from which recovery is possible once the fin has become unstalled. Sometimes slight apparent rudder overbalance may be noticed under asymmetric power when large amounts of rudder trim are used to decrease the foot load on the rudder bar. If this happens the amount of rudder trim should be reduced.

48. **Rudder Tramping**. On some aircraft the onset of rudder overbalance may be shown by ‘tramping’, or a fluctuation in the rudder foot loads. If the yaw is further increased overbalance may occur.

49. **Elevons and Tailerons**. Some aircraft with swept-back wings combine the function of the elevators and ailerons in control surfaces at the wing tips called elevons, or if tail mounted, tailerons. These are designed so that a backward movement of the control column will raise both surfaces and so, acting as elevators, they will raise the nose. If the control column is held back and also moved to one side, the surfaces will remain in a raised position and so continue acting as elevators, but the angular position of each surface changes so that the lift at each wing tip is adjusted to cause a rolling moment in the direction that the control column has been moved. If the control column is held central and then moved to one side the surfaces act as normal ailerons; a subsequent forward movement of the control column will lower both surfaces, maintaining the angular difference caused by the sideways movement of the control column, and the nose will drop while the aircraft is rolling.

The All-Moving (Slab) or Flying Tail

50. At high Mach numbers the elevator loses much of its effectiveness for reasons given in the chapters on high speed flight. This loss of effectiveness is the cause of a serious decrease in the accuracy with which the flight path can be controlled and in the manoeuvrability. To overcome this deficiency the tailplane can be made to serve as the primary control surface for control in the looping plane. When this is done some form of power assistance is usually employed to overcome the higher forces needed to move the tailplane during flight. With the flying tail, full and accurate control is retained at all Mach numbers and speeds. Forward movement of the control column increases the incidence of the tailplane to obtain the upward force necessary to lower the nose. On some aircraft the elevator is retained and is linked to the tailplane in such a way that movement of the tailplane causes the elevator, by virtue of its linkage, to move in the usual direction to assist the action of the tailplane. When no elevator is used the whole is known as a slab tailplane.

The Variable Incidence (VI) Tail

51. This is used on some aircraft as an alternative, and sometimes in addition, to trimming tabs. By suitably varying the incidence of the tailplane any out-of-trim forces can be balanced as necessary. The VI tailplane is generally more effective than tabs at high Mach numbers. Its method of operation is usually electrical; the control being a switch which is spring-loaded to a central off position.

The Vee Tail

52. The Vee, or butterfly, tail is an arrangement whereby 2 surfaces forming a high dihedral angle perform the functions of the conventional horizontal and vertical tail surfaces. The effective horizontal tail area is the area of both surfaces projected on the horizontal plane. The effective vertical tail area is the area of both surfaces projected on the vertical plane. As the lift force from each surface acts normal to its span line, the vertical component acts to provide a pitching moment, and the horizontal component acts to produce a yawing moment. The 2 moveable, portions therefore are capable of performing the functions of both the elevator and the rudder. They are sometimes called a ruddervator. It can be seen that if both surfaces are moved up or down an equal amount, the net result is a change in the vertical force component only, and a pitching moment only results. If the 2 surfaces are moved equal amounts in opposite directions, the result is a change in the net horizontal force component only, and a yawing moment only results. Any combination of the 2 movements results in combined pitching and yawing moments.

53. The elevator control in the cockpit is connected to give an equal deflection in the same direction. The rudder control is connected to give equal deflections in opposite directions to the 2 surfaces. The 2 cockpit controls are connected to the 2 surfaces through a differential linkage or gearing arrangement. Thus the Vee tail performs the horizontal and vertical tail control functions with normal cockpit controls. Some of the advantages claimed are:

a. Weight saving - less total tail surface required.

b. Performance gain - less total tail surface and lower interference drag, as only 2 surfaces intersect the fuselage.

c. Removal of the tail from the wing wake and downwash.

d. Better spin recovery, as the unblanketed portion of the tail acts both to pitch the aircraft down and to stop the rotation.

AIRBRAKES

General

54. Jet engined aircraft, having no propeller drag when the engine is throttled back, have comparatively low drag and lose speed only slowly. Further, having eventually reached the desired lower speed, any slight downward flight path causes an immediate and appreciable increase in speed.

55. An air brake is an integral part of the airframe and can be extended to increase the drag of an aircraft at will, enabling the speed to be decreased more rapidly, or regulated during a descent. On some aircraft the undercarriage may be lowered partially or completely to obtain the same effect.

56. Although the area of the air brakes on a typical fighter is small, considerable drag is produced at high speeds. For example, an air brake with an assumed C_D of 1.2 and a total area of about 2.5 sq ft produces a drag of about 5,700 lb when opened at 500 kt at sea level. This figure is indicative of the large loads imposed on an aircraft when flying at high indicated speeds. The effectiveness of an air brake varies as the square of the speed and therefore at about 120 kt the same air brake gives a drag of about 330 lb only. The decelerating effect of air brakes can be seen from figures obtained from an aircraft flying at 400 kt at low altitude. With the air brakes in and power off the aircraft takes 2 min 58 sec to slow to 150 kt; with air brakes out the time is reduced to 1 min 27 sec.

57. Ideally, air brakes should not produce any effect other than drag, although on some American aircraft the air brakes are designed to produce an automatic nose-up change of trim when opened. In practice, however, the opening of most air brakes is accompanied by some degree of buffet, with or without a change of trim; the strength of these adverse effects is usually greatest at high speeds, becoming less as the speed decreases.

Effect of Altitude on Effectiveness

58. Air brakes derive their usefulness from the fact that they are subjected to dynamic pressures - the 1/2rV2 effect - and so provide drag in proportion to their area. At high altitudes therefore, the effectiveness of all air brakes is much reduced since the drag, which is low in proportion to the TAS, takes longer to achieve a required loss in speed, ie the rate of deceleration is reduced.

59. An air brake which develops, say, 2,000 lb drag at a stated IAS/TAS at sea level will develop the same drag at the same IAS at high altitude; but whereas the TAS at sea level was equal to the IAS, the TAS at altitude may be as much as 2 or more times the IAS. Since the drag is required to decrease the kinetic energy, which is proportional to the TAS, it is apparent that the decelerating effect of the air brake (proportional to the IAS) is decreased, eg the time taken to decelerate over a given range of IAS will be doubled at 40,000 ft compared to that at sea level since the IAS at 40,000 ft is about half the TAS.

BRAKE PARACHUTE

General

60. Brake parachutes are used to supplement the aircraft's wheel brakes and so reduce the length of the landing run. In general they produce enough drag to cause a steady rate of deceleration varying from about 0.25g to 0.35g depending upon the particular installation. Below 60 to 70 kt the drag, varying as the square of the speed, falls to a much lower figure and the wheel brakes become the primary means of deceleration.

Parachute Diameter

61. The diameter of the parachute depends on the weight and size of the aircraft. For aircraft with a landing weight of around 5,000 kg, the 'flying' diameter of the parachute is from 2 - 3 m. At a touchdown speed of 130 kt this gives a drag of about 1,250 kg and a deceleration rate of about 0.25g.

62. For large aircraft with landing weights around 50,000 kg the flying diameter of the brake parachute is about 11 m. This produces, at a touchdown speed of about 150 kt, a drag of some 25,000 kg and an initial rate of deceleration of about 0.35g.

Cross-wind Landings

63. When used in a cross-wind landing the parachute aligns itself along the resultant between the vectors representing the forward speed of the aircraft and the 90° component of the cross-wind vector (see Fig 11). This causes a yawing moment which increases the weather-cock characteristics of the aircraft. For 90° cross-wind components of up to 20 kt the effect is small and can easily be countered by the pilot; at higher cross-wind speeds it becomes progressively more difficult to keep the aircraft straight. As the aircraft decelerates, the flying angle between the parachute and the centre line of the aircraft increases, but the retarding force of the parachute will decrease with the reduction in V^2. Thus the overall effect of decreasing speed is a reduction in the weathercocking tendency due to the brake parachute.

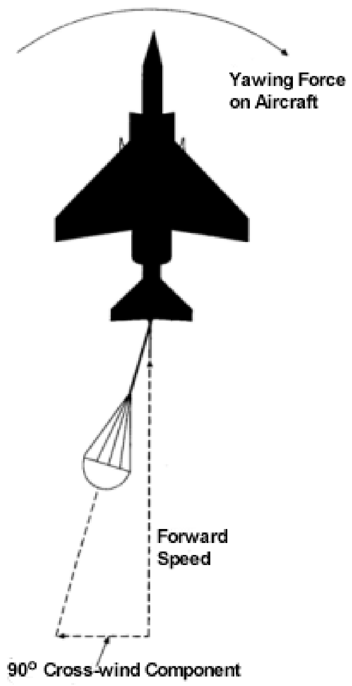


Fig 11 Effect of Cross-wind

64. Any difficulty in directional control tends to occur fairly early in the landing run, although not necessarily at the highest speed; this is mainly due to the very small flying angle and the relatively high rudder effectiveness. Tyre sideslip due to the side load imposed by the parachute may be another significant factor.

Jettisoning of Brake Parachute

65. At any time after the parachute has been streamed it can be disconnected or jettisoned by the pilot in an emergency. It is also usual to jettison the parachute at the end of the landing run.

Inadvertent Streaming in Flight

66. If the parachute is opened inadvertently at high speed the opening load causes failure of a weak link and the parachute breaks away from the aircraft. If opened too early on the approach it can be disconnected by the pilot.

SUMMARY

Flight Controls

67. The main control surfaces are:

a. Rudder.
b. Elevator.
c. Aileron.

On some aircraft the effect of 2 of these controls is combined in a single set of control surfaces, eg: elevons, ruddervator and tailerons (tail mounted 'elevons').

68. Control power and effectiveness is decided by:

a. Size and shape of the control.
b. Deflection angle.
c. EAS^2.
d. Moment arm.

69. Aerodynamic balance is a means of reducing the hinge moment and thereby reducing the physical effort experienced in controlling an aircraft. The most common forms of aerodynamic balance are:

a. Horn balance.
b. Inset hinge.
c. Internal balance.
d. Various types of tab balance.

70. Flutter can be prevented by:

a. Mass balancing.
b. Increasing structural rigidity.
c. Irreversible controls.

71. The main considerations for control requirements are:

a. Control force.
b. Control movement.
c. Control harmony.

72. Different control responses are given different terms. The ailerons are normally described as a rate control, and the rudder and elevator as displacement controls.

73. Methods of overcoming adverse aileron yaw are:

a. Differential ailerons.
b. Frise ailerons.
c. Control coupling.
d. Spoilers.

74. Some advantages claimed for the Vee tail are:

a. Weight saving.
b. Performance gain.
c. Removal of the tail from the wing wake and downwash.
d. Better spin recovery.

CLIMBING AND GLIDING

Introduction

1. This chapter deals primarily with the principles of flight involved in both climbing and gliding, but in considering the factors affecting the climb, some performance details are discussed.

CLIMBING

General

2. During a climb an aircraft gains potential energy by virtue of elevation; this is achieved by one or, a combination of two means:

a. The expenditure of propulsive energy above that required to maintain level flight.

b. The expenditure of aircraft kinetic energy, ie loss of velocity by a zoom.
Zooming for altitude is a transient process of exchanging kinetic energy for potential energy and is of considerable importance for aircraft which can operate at very high levels of kinetic energy. However, the major portion of climb performance for most aircraft is a near steady process in which additional propulsive energy is converted into potential energy.

Forces in the Climb

3. To maintain a climb at a given EAS more power has to be provided than in level flight; this is first to overcome the drag as in level flight IP_{REQ} = D x V), secondly to lift the weight at a vertical speed, which is known as the rate of climb, and thirdly to accelerate the aircraft slowly as the TAS steadily increases with increasing altitude.

$P_{REQ} = DV + WV_C + WV\frac{a}{g}$ where V_C is the rate of climb and a is the acceleration.

The acceleration term can be ignored in low performance aircraft but has to be taken into account in jet aircraft with high rates of climb.

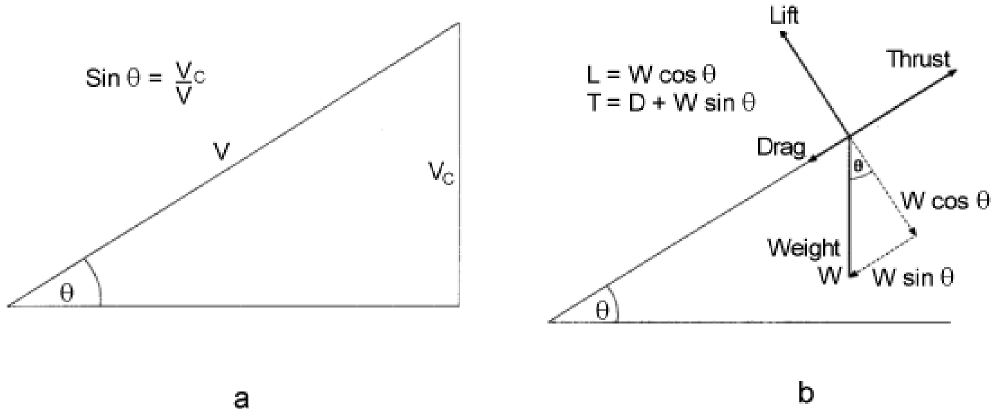


Fig 1 Forces in the Climb

4. In Fig 1b it can be seen that in the climb lift is less than weight. If this is so then the lift dependent drag is less than at the same speed in level flight. It can be seen from the figure that L = W cosθ. However, it is still considered sufficiently correct to assume that lift equals weight up to about 15° climb angle (since cos 15° is still 0.9659, the error due to this assumption is less than 2%).

5. Figs 1a and b can be used to show that rate of climb is determined by the amount of excess power and the angle of climb is determined by the amount of excess thrust left after opposing drag.

In Fig 1a: $\sin\theta = \frac{\text{rate of climb}}{V}$

In Fig 1b: $\sin\theta = \frac{\text{thrust} - \text{drag}}{\text{weight}}$

Since θ is the same in each case:

$$\frac{\text{rate of climb}}{V} = \frac{\text{thrust} - \text{drag}}{\text{weight}}$$

Therefore,

$$\text{rate of climb} = \frac{V(\text{thrust} - \text{drag})}{\text{weight}}$$

$$= \frac{P_{AV} - P_{REQ}}{\text{weight}}$$

$$= \frac{\text{excess power}}{\text{weight}}$$

6. In practice aircraft do not, for varying reasons, (eg engine cooling, avoidance of an exaggerated attitude) always use the exact speed for maximum rate of climb. In jet aircraft this speed is quite high and at low altitude is not very critical due to the shape of the power available curve (see para 8). In piston aircraft the speed is much lower and is normally found to be in the vicinity of the minimum drag speed.

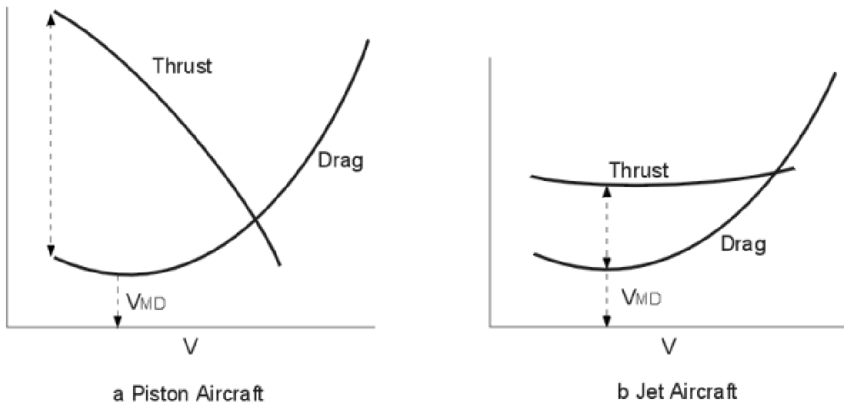


Fig 2 Maximum Angle of Climb

7. When the maximum angle of climb is required it can be seen from Fig 1b, where $\sin\theta = \frac{\text{thrust} - \text{drag}}{\text{weight}}$, that the aircraft should be flown at the speed which gives the maximum difference between thrust and drag. For piston aircraft, where thrust is reducing as speed is increased beyond unstick, the best speed is usually as low as is safe above unstick speed. For a jet aircraft, since thrust varies little with speed, the best speed is at minimum drag speed (Fig 2).

Power Available and Power Required

8. The thrust horsepower available curve is calculated by multiplying the thrust (1b) by the corresponding speed (fps) and dividing by 550. The thrust power curve for a jet engine differs from that of a piston engine as shown in the upper curves of Fig 3. The main reason for this difference is that the thrust of a jet engine remains virtually constant at a given altitude, irrespective of the speed; therefore when this constant thrust is multiplied by the appropriate air speed to calculate thrust horsepower, the result is a straight line. The piston engine, on the other hand, under the same set of circumstances and for a given bhp, suffers a loss of thrust horsepower at both ends of its speed range because of reduced propeller efficiency. The thrust horsepower available curves are representative of a more powerful type of Second World War piston engine fighter and a typical jet fighter having a high subsonic performance.

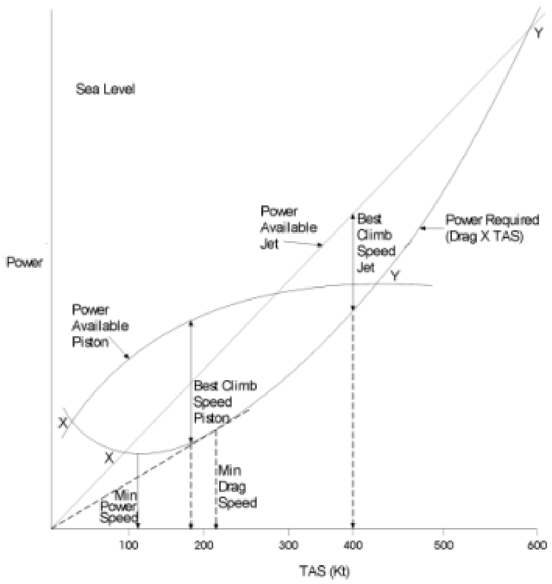


Fig 3 Typical Power Available and Power Required Curves at Sea Level

9. The horsepower required to propel an aircraft in level flight can be found by multiplying the drag (1b) by the corresponding TAS (fps) and dividing by 550. The lower curve of Fig 3 is a typical example and can be assumed to apply to both a piston or jet-propelled airframe, ie the airframe drag is the same irrespective of the power unit used. Note that the speed for minimum drag, although low, is not the lowest possible nor is it that for minimum power. The increase in power required at the lowest speed is caused by the rapidly rising effects of induced drag.

Climbing Performance

10. The vertical distance between the power available and the power required curves represents the power available for climbing at the particular speed. The best climbing speed (highest rate of climb) is that at which the excess power is at a maximum; so that, after expending some power in overcoming the drag, the maximum amount of power remains available for climbing the aircraft. For the piston engine aircraft the best speed is seen to be about 180 kt, and for the jet about 400 kt. Notice that in the latter case a fairly wide band of speeds would still give the same amount of excess power for the climb but in practice the highest speed is used since better engine efficiency is obtained. At the intersection of the curves (points X and Y) all the available power is being used to overcome drag and none is available for climbing; these points therefore represent the minimum and maximum speeds possible for the particular power setting.

11. If power is reduced the power available curve is lowered. Consequently the maximum speed and maximum rate of climb are reduced, while the minimum speed is increased. When the power is reduced to the point when the power available curve is tangential to the power required curve, the points X and Y coincide and the aircraft cannot climb.

Effect of Altitude on Climbing

12. The thrust horsepower of both jet and piston engines decreases with altitude. Even if it is possible to prolong sea-level power to some greater altitude by supercharging or some other method of power boosting, the power will inevitably decline when the boosting method employed reaches a height at which it can no longer maintain the set power.

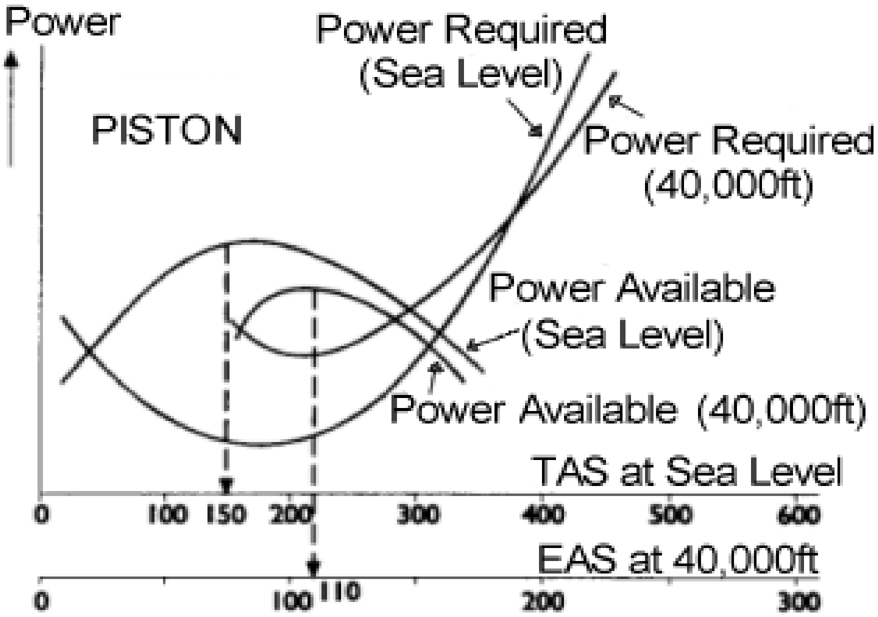


Fig 4 Effect of Altitude on Typical Power Available and Power Required Curves (Piston).

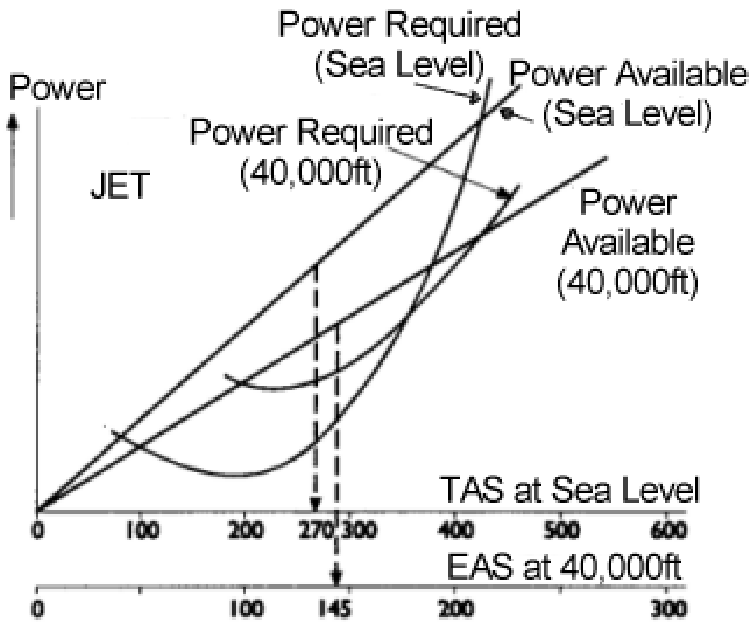


Fig 4 Effect of Altitude on Typical Power Available and Power Required Curves (Jet).

13. At the highest altitudes the power available curves of both types of engine are lowered as shown in Fig 4 and the power required curve is displaced upwards and to the right. Notice that the power required to fly at the minimum drag speed is increased; this effect is caused by the fact that although the minimum drag speed, in terms of EAS, remains the same at all heights, the speed used in the calculation of thp is the TAS, which increases with altitude for a given EAS. Therefore the power required to fly at any desired EAS increases with altitude. From Fig 4 it may be seen that the speed for the best rate of climb reduces with altitude and the range of speeds between maximum and minimum level flight speeds is also reduced.

NOTE:

The height of 40,000 ft used in Fig 4 was chosen because at that height EAS = $\frac{1}{2} \times$ TAS; a piston engine would not normally operate at that height.

14. **Ceilings**. The altitude at which the maximum power available curve only just touches the power required curve and a sustained rate of climb is no longer possible is known as the absolute ceiling. It is possible to exceed this altitude by the zoom climb technique which converts the aircraft's kinetic energy (speed) to potential energy (altitude). Another ceiling is the service ceiling which is defined as the altitude at which the maximum sustained rate of climb falls to 500 fpm (100 fpm for a piston aircraft).

Operating Data Manuals

15. On older, simpler types of aircraft some basic take-off and climb data was given briefly in either narrative or tabular form in the Aircrew Manual. Now, with modern complex aircraft, take-off and climb data is much more comprehensive and is given in the aircraft Operating Data Manual either in graphical or detailed tabular form.

GLIDING

Forces in the Glide

16. For a steady glide, with the engine giving no thrust, the lift, drag and weight forces must be in equilibrium (ignoring the deceleration term due to maintaining a constant IAS). Fig 5 shows that the weight is balanced by the resultant of the lift and drag; the lift vector, acting as it does at right angles to the path of flight, will now be tilted forward while the drag vector still acts parallel to the path of flight. To maintain air speed energy must be expended to overcome this drag. When the engine is no longer working the source of energy is the potential energy of the aircraft (ie the altitude).

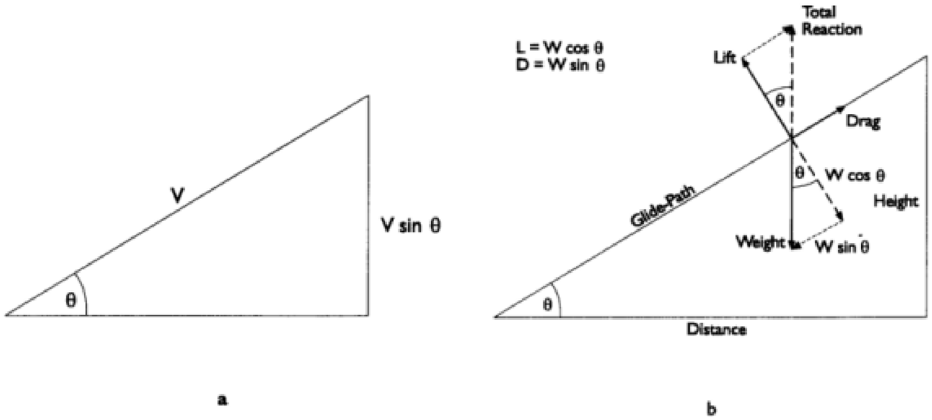


Fig 5 Forces in the Glide

17. The aircraft can either be made to have as low a rate of descent as possible, which will be obtained at the speed which requires least power, or it can be made to have as shallow an angle of glide as possible which will be the speed where least drag is produced (compare rate and angle of climb).

Gliding for Endurance

18. It is rare that aircraft, other than sailplanes, require to glide for minimum rate of sink. From Fig 5a it can be seen that for minimum rate of descent, V sin q must be as small as possible. But D X V (ie power required) = WV sinθ (ignoring the deceleration term due to maintaining a constant IAS). Therefore, for a given weight, the rate of descent is least at the speed where the power required (DV) is least.

Gliding for Range

19. Note that the triangle formed by lift, drag and total reaction is geometrically similar to that formed by distance, height and glidepath. Now, if distance is to be maximum, gliding angle must be minimum. θ is minimum when Cotθ is maximum and, from Fig 5b, it can be seen that:

$$\mathrm{Cot}\ \theta = \frac{\mathrm{W}\ \cos\theta}{\mathrm{W}\ \sin\theta} = \frac{\mathrm{L}}{\mathrm{D}} = \frac{\mathrm{C_L}}{\mathrm{C_D}}$$

Therefore the best angle of glide depends on maintaining an angle of attack which gives the best lift/drag ratio. Therefore for maximum distance the aircraft should be flown for minimum drag. For angles of glide of less than 15°, cosθ approximates to 1 and so it is reasonable to use the level flight power curves. If the angle of descent exceeds about 15° then it is no longer sufficiently correct to assume that lift equals weight. Theactual lift needed is less and so the gliding speed is reduced by a factor of √cosθ. Since, ignoring compressibility, drag depends on EAS, the best gliding speed at a given weight is at a constant EAS regardless of altitude. The rate of descent will, however, get less at lower altitudes as the TAS decreases.

Effect of Wind

20. Since, in a glide for minimum rate of descent the position of the end of the glide is not important, wind will not affect gliding for endurance. However, when gliding for range the all-important target is the point of arrival; the aim is maximum distance over the ground. In still air this is achieved by flying for minimum drag as explained in para 19. The effect of a head wind will be to decrease the ground distance traveled by approximately the ratio of the wind speed compared to the TAS. A calculated increase of airspeed reducing the time the wind effect could act could improve the ground distance traveled. Similarly, if there were a tailwind the ground distance traveled would be increased. A reduction of speed towards which gives the minimum rate of descent could be beneficial

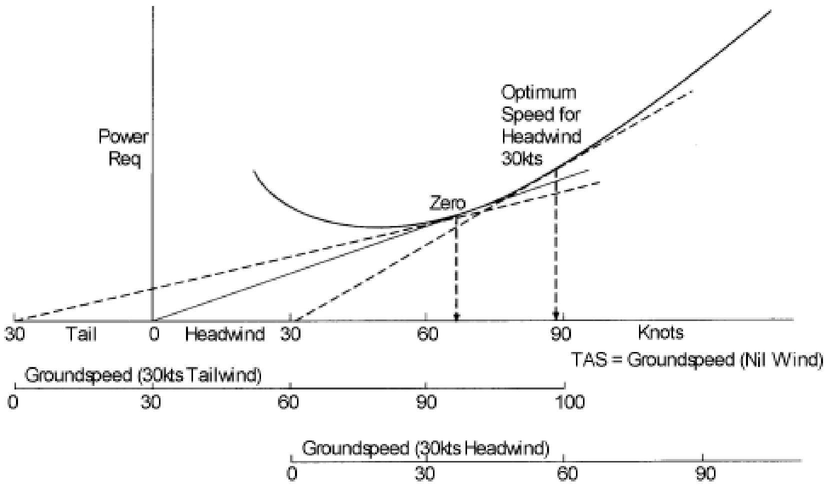


Fig 6 The Graphical Method of Finding Maximum Range Gliding Speeds

because it would allow more time for the wind to act on the aircraft. The graphical method of finding the best speed to glide for maximum range in the presence of a head or tailwind is the same as that for finding the optimum range speed for a piston aircraft. From the wind value along the TAS axis the tangent should be drawn to the power required curve (see Fig 6).

Effect of Weight

21. Variation in the weight does not affect the gliding angle provided that the speed is adjusted to fit the auw. The best EAS varies as the square root of the auw. A simple method of estimating changes in the EAS to compensate for changes in the auw up to about 20% is to decrease or increase the air speed by half the percentage change in the auw. For example, a weight reduction of 10% necessitates a drop in air speed of 5%; an increase of weight of the same amount would entail a 5% increase.

22. Fig 7 shows that an increase in the weight vector can be balanced by lengthening the other vectors until the geometry and balance of the diagram is restored. This is done without affecting the gliding angle. The higher speed corresponding to the increased weight is provided automatically by the larger component of the weight acting along the glide path; and this component grows or diminishes in proportion to the weight. Since the gliding angle is unaffected, the range is also unchanged in still air. Where weight does affect the range is when there is a tailwind or headwind component. The higher TAS for a heavier weight allows less time for the wind to affect the aircraft and so it is better to have a heavier aircraft if gliding for range into wind. If minimum rate of descent is required then the aircraft should be light. The lower drag requires a less rapid expenditure of power which is obtained from the aircraft's potential energy (height).

23. Although the range is not affected by changes in weight, the endurance decreases with increase of weight and vice versa. If two aircraft having the same L/D ratio but with different weights start a glide from the same height, then the heavier aircraft gliding at a higher EAS will cover the distance between the starting point and the touchdown in a shorter time; both will, however, cover the same distance in still air. Therefore the endurance of the heavier aircraft is less.

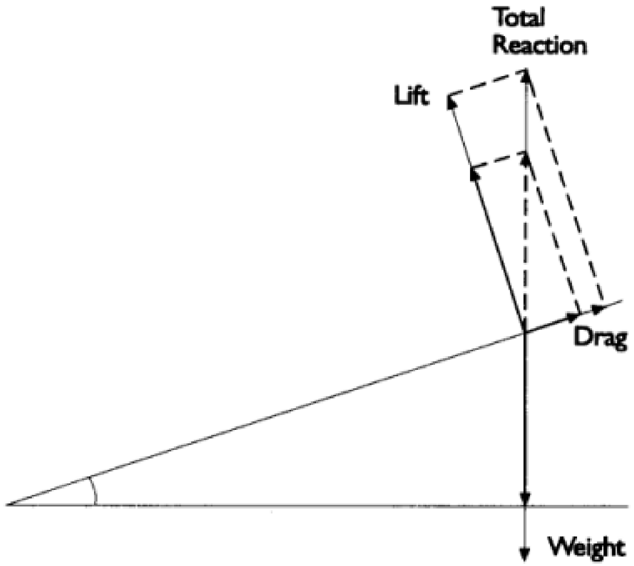


Fig 7 Effect of Weight on Glide

24. Usually the exact distance covered on the glide is not vitally important, therefore the gliding speed stated in the Aircrew Manual is a mean figure applying to the lower weights of a particular aircraft and giving the best all-round performance in the glide.

TOPIC-3 : BASIC PRINCIPLES OF HELICOPTER FLIGHT

CONTROL IN FORWARD FLIGHT

Introduction

1. When torque is applied to the rotor shaft of a helicopter there is an equal and opposite torque reaction applied to the helicopter by the rotor shaft. If the torque reaction is not balanced the helicopter fuselage will turn in the opposite direction to the rotor. In this chapter torque reaction and the solution to it will be discussed. The forces in the hover and in forward flight, and transition from forward flight to the hover will also be discussed.

Torque Reaction

2. The torque reaction on a single rotor helicopter is shown in Fig 1. A torque compensating force at the tail is the most common method of balancing torque reaction and the force is provided by a tail rotor or shrouded tail rotor (Fenestron).

3. **The Tail Rotor**. The tail rotor is mounted vertically at the rear of the fuselage and clear of the main rotor, see Fig 2. It is driven from the main gearbox by a tail rotor drive shaft and geared such that the shaft revolves at a very high speed compared to the main gearbox and the tail rotor. The reason for an increase in the rpm of the tail rotor drive shaft is to allow the construction of it to be flimsier because the torque, which is directly proportional to rpm, is reduced. It is also easier to balance the shaft if it rotates at high rpm.

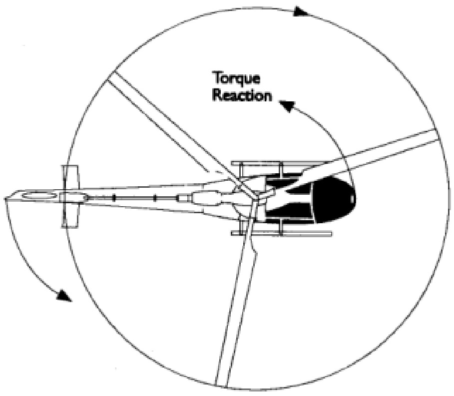


Fig 1 Torque Reaction

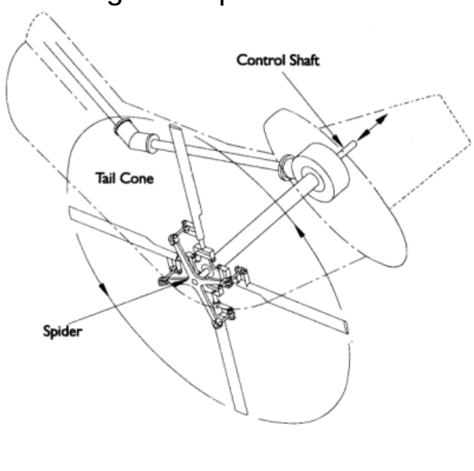


Fig 2 Conventional Tail Rotor

4. **The Shrouded Tail Rotor.** The shrouded tail rotor, or Fenestron, is a high speed, variable pitch ducted fan mounted in a cambered fin. It has many features in common with a propeller but it has control characteristics similar to a tail rotor, see Fig 3 and Vol 1, Pt 2, Sect 2, Chap 1.

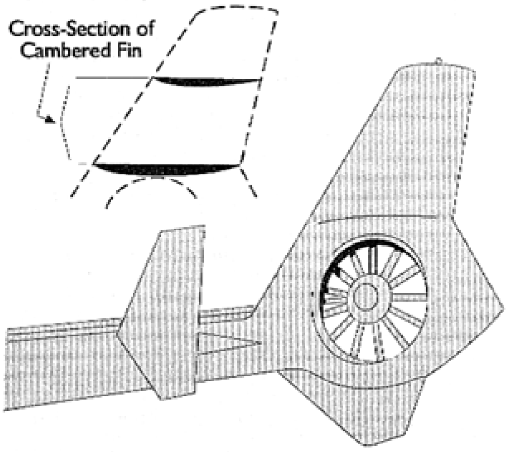


Fig 3 Shrouded Tail Rotor (Fenestron)

5. **Control Mechanism**. When the moment of the tail rotor thrust equals the torque reaction couple, then the fuselage will maintain a constant direction. As the torque reaction is not constant some means must be provided to vary the thrust from the tail rotor. This is achieved by the pilot moving yaw pedals which collectively change the pitch and, therefore, the thrust from the tail rotor.

6. **Additional Tail Rotor Functions**. The tail rotor has the following additional functions:

a. Heading control in the hover is achieved by increasing or decreasing tail rotor thrust so that torque reaction is not balanced and the helicopter is able to turn about the rotor shaft.

b. Balance in forward flight is adjusted by tail rotor thrust in a similar fashion to the rudder control of an aeroplane.

c. In power off flight (autorotation) there is no torque reaction. The rotor is turning and there is friction in the transmission which tends to turn the helicopter in the same direction as the rotor. The turn is prevented by negative pitch on the tail rotor which produces thrust opposite to that in powered flight.

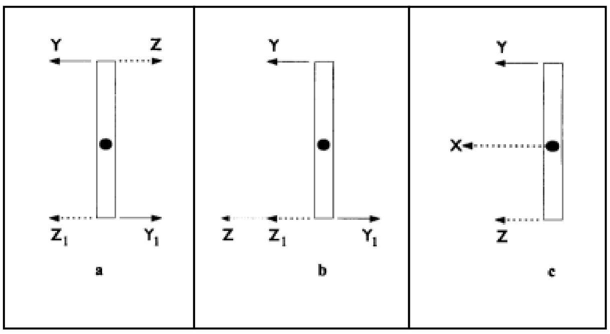


Fig 4 Tail Rotor Drift

Tail Rotor Compensation

7. **Tail Rotor Drift**. If a fuselage is being turned by a couple YY_1, about a point, the rotation will stop if a couple ZZ_1, of equal value, acts in the opposite direction, Fig 4a. The rotation would also stop if a single force ZZ_1 was used to produce a moment equal to the couple YY_1, Fig 4b, but there would now be a side force X on the pivot point, Fig 4c. This side force is known as tail rotor drift and, unless corrected, it would result in the helicopter moving sideways over the ground.

8. **Correcting For Tail Rotor Drift.** Tail rotor drift can be corrected by tilting the rotor disc away from the direction of the drift. This can be achieved by:

a. The pilot making a movement of the cyclic stick.

b. Rigging the controls so that when the stick is in the centre the disc is actually tilted by the correct amount.

c. By mounting the gearbox so that the drive shaft to the rotor is offset.

9. **Tail Rotor Roll.** If the tail rotor is mounted on the fuselage below the level of the main rotor the tail rotor drift corrective force being produced by the main rotor will create a rolling couple with the tail rotor thrust, causing the helicopter to hover one wheel or skid low. The amount of roll depends upon the value and angle of the tail rotor thrust and the vertical separation between main and tail rotors. In the hover, the helicopter will roll about the horizontal couple until the movement is balanced by the couple of the vertical component of total rotor thrust and the helicopter all up weight, see Fig 5.

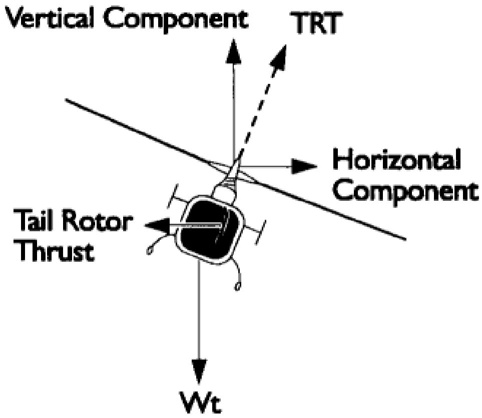


Fig 5 Tail Rotor Roll

A helicopter is usually designed so that the tail rotor is in line with the main rotor head at forward speed. In the hover, tail rotor roll is accepted.

Rotor Configurations

10. It is possible to counteract torque reaction by using twin main rotors which may be mounted co-axially and revolve in opposite directions, or in a fore and aft configuration or even side-by-side. In all cases synchronization of the rotors is vital for the maintenance of directional control.

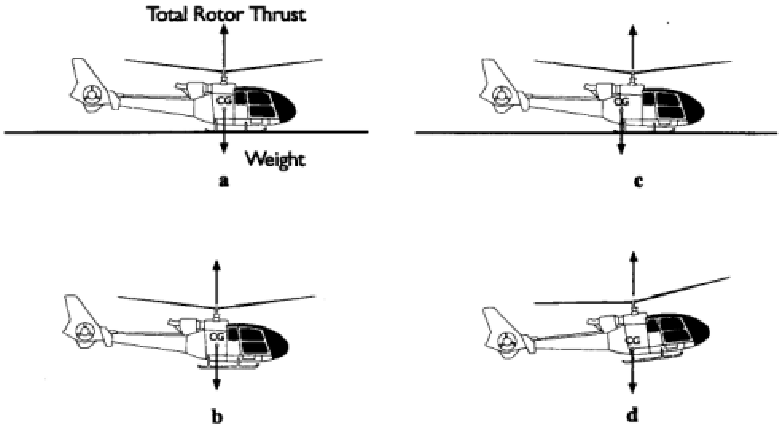


Fig 6 Forces in Balance - Hover

Forces in the Hover and in Forward Flight

11. **Forces in Balance - Hover**. In a free air hover the total rotor thrust will be acting vertically upwards through the axis about which the blades are rotating and at right angles to the tip path plane. Weight will be acting vertically downwards through the CG, Fig 6a. If the helicopter is loaded to position the CG immediately below the blades' axis of rotation, and discounting downdraft on any horizontal surfaces, no change in fuselage attitude will occur when the helicopter leaves the ground, Fig 6b. If, however, the CG is not below the axis of rotation, Fig 6c, a couple will exist between total rotor thrust and the weight, and the fuselage will pitch until both forces are in line, Fig 6d. It should be noted that a helicopter in the hover often adopts a nose-up attitude in any case, irrespective of the position of the CG. This happens because downwash from the main rotor exerts a force on the tail stabilizer causing a tail-down moment. In still air conditions the nose-up attitude is quite marked but as wind speed increases the vertical component of rotor downwash is reduced and the helicopter adopts a more level attitude. Hovering attitude is also affected by flapback which is discussed in para 28.

12. **Forces in Balance - Forward Flight.** If a helicopter moves from a free air hover into forward flight with no change in the fuselage attitude, the rotor disc will be tilted forward and the disposition of forces will be as shown in Fig 7a. Total rotor thrust is now inclined forward and produces a nose-down pitching moment about the CG. The vertical components of TRT and AUW remain in line but a couple now exists between the horizontal component of TRT and fuselage parasite drag as the aircraft speed increases. The fuselage will pitch forward but the moment will now be opposed by the vertical component of TRT and Wt with the forces resolved as in Fig 7b. The fuselage will only pitch forward until the couples are in balance. This will occur when TRT is in line with the CG. CG therefore controls the position of the fuselage in relation to the disc. This relationship is affected in forward flight by the negative lift effect of the tail stabilizer and the moment exerted by it.

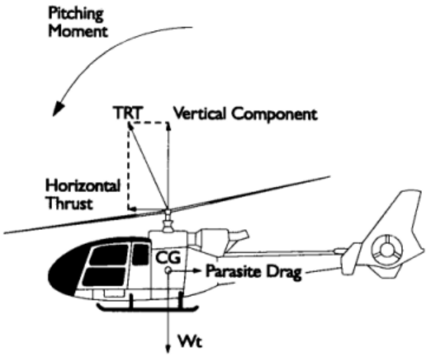


Fig 7a Level Attitude With Pitching Moment

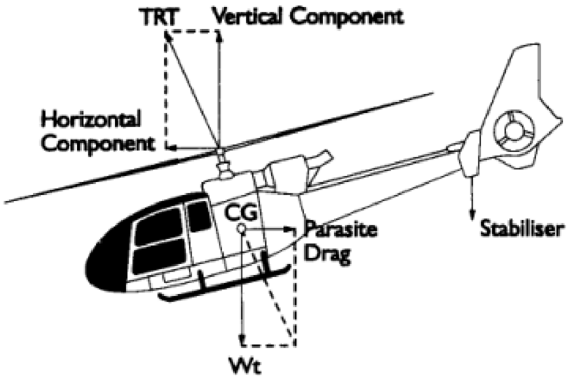


Fig 7b Forces in Balance

Transition

13. To achieve forward flight the rotor disc is tilted so that TRT produces not only a vertical force to balance the weight but also a horizontal force in the direction of flight. The change of state from the hover to forward flight, or from forward flight to the hover, is known as transition.

14. **The Sequence of Events During Transition**. As the helicopter moves initially from the hover the disc, and hence TRT, is tilted. The vertical component of TRT is reduced and becomes less than Wt and to prevent the helicopter from descending TRT is increased with more collective pitch. The power required increases, see Fig 8. As the aircraft accelerates the fuselage acts pendulously below the main rotor and pitches nose down, Fig 9.

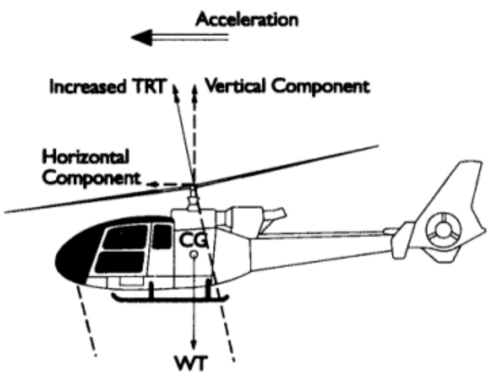


Fig 8 Forces During Transition

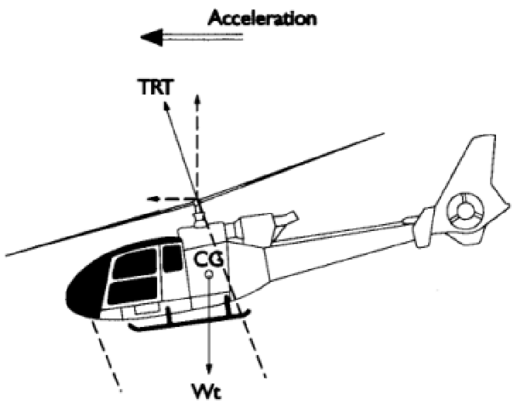


Fig 9 Fuselage Pendularity

Translational Lift

15. When a helicopter is in a free air hover in still air conditions, for a given rotor rpm (Rrpm) a certain value of collective pitch, say 8°, will be required to support it in the air. A column of air, the induced flow, will be continually moving down towards the rotor disc, and thus downward flow of air must be considered when determining the direction of the airflow in relation to the blades, see Figs 10a, b. It will be noted that the angle of attack, say 4°, is less than the pitch angle. The angle of attack depends on the value of the induced flow; if the induced flow is removed, the angle of attack becomes the same as the pitch angle.

16. If the effect of a helicopter facing into a 20Kt wind is considered, and it is assumed that it is possible for it to maintain the hover without tilting the disc, the horizontal flow of air (wind) will blow across the vertically induced column of air and deflect it down-wind before it reaches the disc. The column of air which was flowing down towards the disc will, therefore, be modified and gradually be replaced by a mass of air which is moving horizontally across the disc. The rotor will act on this air mass to produce an induced flow but the velocity of the induced flow will be greatly reduced, see Fig 11.

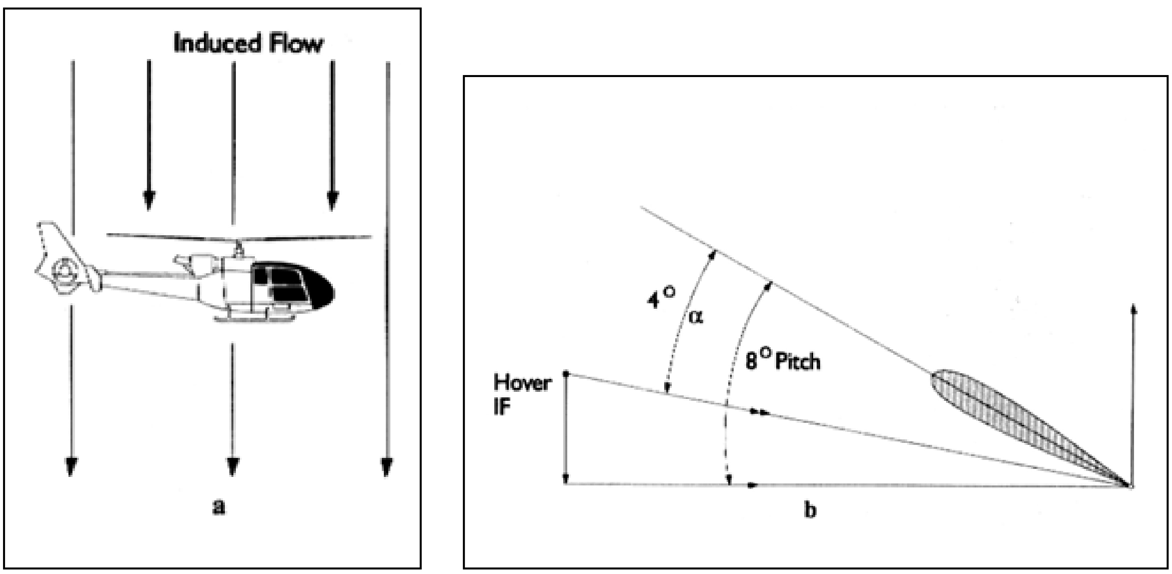


Fig 10 Induced Flow from Vertically Above

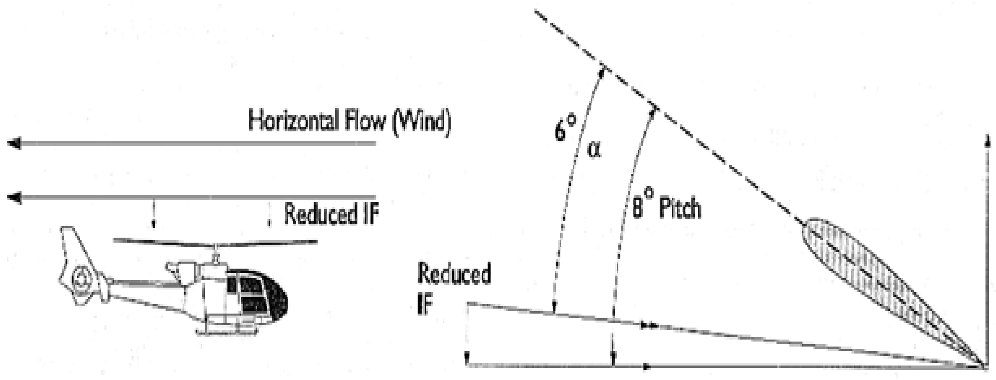


Fig 11 Induced Flow with Air Moving Horizontally

Therefore, airflow parallel to the disc must reduce the value of the induced flow, increase the angle of attack and, therefore, rotor thrust.

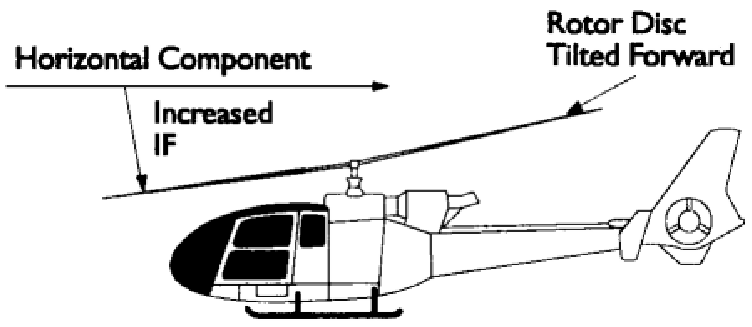


Fig 12 Induced Flow with Disc Tilted Forward

17. To maintain the hover condition when facing into wind, the disc must be tilted forward. The horizontal flow of air will not now be parallel to the disc, and a component of it can now be considered to be actually passing through the disc at right angles to the plane of rotation, effectively increasing the induced flow, see Fig 12. To consider the extreme case if the rotor disc were tilted 90° to this horizontal flow of air, then all of it would be passing through the disc at right-angles to the plane of rotation.

18. As described in para 16, the effect of the horizontal airflow across the disc when hovering into wind is to reduce the induced flow but, because the disc has had to be tilted forward, (para 17) a component of this horizontal airflow will now be passing through the disc, effectively increasing the induced flow; both of these effects must now be taken into consideration to give the total flow towards the disc and to determine the direction of the airflow relative to the blades. Provided the reduction in the induced flow caused by the flow parallel to the disc is greater than the increase caused by the component of horizontal airflow passing through the disc, then the relative airflow will be nearer the plane of rotation than when the helicopter is in the hover, the angle of attack will increase and the aircraft will climb. Therefore, the collective pitch can be decreased to say, 7, while maintaining an angle of attack of 5. As the relative airflow moves nearer the plane of rotation, the total reaction must move forward. There will, therefore, be less rotor drag, and rotor rpm can be maintained with less power.

19. The reduction in induced flow, translational lift, first takes effect when air moves towards the disc at approximately 12Kt. The reduction is appreciable at first, and although it continues to reduce as the velocity of the horizontal airflow increases, the rate at which it reduces becomes progressively less because there is less induced flow to be influenced. If induced flow is plotted against forward speed, the graph appears as shown in Fig 13a.

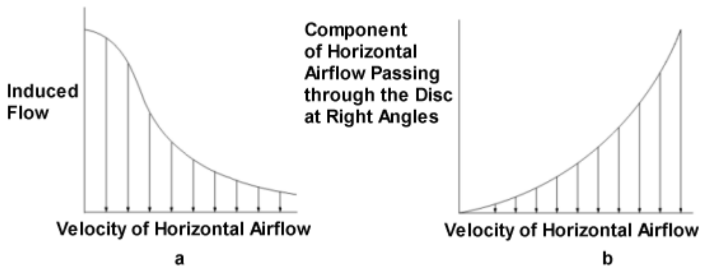


Fig 13 Variation of Induced Flow and Component of Horizontal Airflow Passing Through the Disc with Forward Speed

20. The rotor disc has to be tilted forward to provide a thrust component equal to parasite drag. Parasite drag is low at low forward speed so only a small tilt of the disc is required to provide a balancing amount of thrust and, with only a small tilt of the disc, only a small component of the horizontal airflow will be passing through the disc at right angles to the plane of rotation. Because the parasite drag increases as the square of the speed, the greater must be the amount that the disc must be tilted to provide the necessary increase in thrust and, as the horizontal airflow approaching the disc increases, the greater will be the component of it passing through the disc at right angles to the plane of rotation, see Fig 13b. If the curves in Figs 13a and b are now transferred to one graph it will be seen that the total flow of air at right angles to the plane of rotation at first decreases and then increases again, becoming a minimum when the two airflows have the same value, see Fig 14. As the flow of air through the disc decreases, less collective pitch and power will be required to maintain the required angle of attack. When the flow of air through the disc begins to increase again, then collective pitch and power must be increased if the required angle of attack is to be maintained.

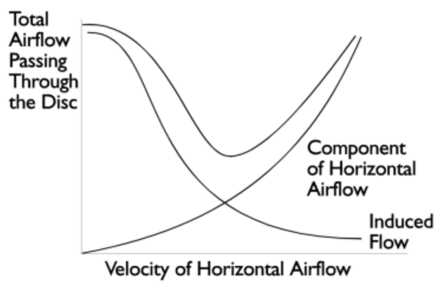


Fig 14 Variation of Total Airflow Through the Disc with Forward Flight

Summary of Transition

21. The sequence of events as a helicopter moves into forward flight is summarized as follows:

a. The cyclic stick is moved forward to tilt the disc and the TRT forward.

b. The vertical component of TRT is reduced and the collective pitch must be increased to maintain height. More power is required.

c. As airspeed increases the disc flaps back. The disc attitude is maintained by increasing forward cyclic control.

d. As airspeed increases inflow roll tilts the disc to the advancing side. The disc attitude is maintained by cyclic control to the retreating side.

e. As airspeed increases the TRT increases with increased translational lift and the pilot lowers the collective to maintain height. Less power is required.

f. During power changes the changing torque reaction is balanced by movement of the yaw pedals.

Transition From Forward Flight to Hover

22. In order to decelerate a helicopter from steady level flight to the hover the balance of forces must be changed. The general method of coming to the hover from forward flight is by the pilot executing a flare by tilting the disc in the opposite direction to that in which the helicopter is moving. The handling techniques needed to control the manoeuvre differ from those required for a more gentle transition.

23. **The Flare.** To execute a flare the cyclic stick is moved in the opposite direction to that in which the helicopter is moving. The harshness of the flare depends upon how far the stick is moved. The flare will produce a number of effects.

24. **Flare Effects.** The following effects occur during the flare:

a. **Thrust Reversal.** By tilting the disc away from the direction of flight the horizontal component of total rotor thrust will now act in the same direction as parasite drag causing the helicopter to slow down very rapidly, see Fig 15a. The fuselage will respond to this rapid deceleration by pitching up because reverse thrust is being maintained whilst parasite drag decreases. If no corrective action is taken the disc will be tilted further still, adding to the deceleration effect, Fig 15b.

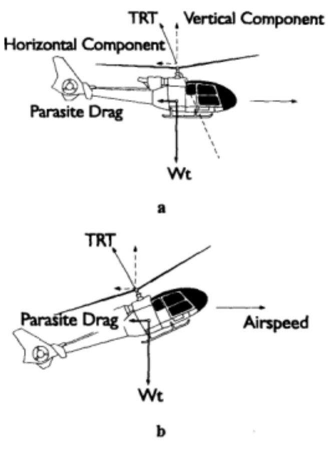


Fig 15 The Flare Effect

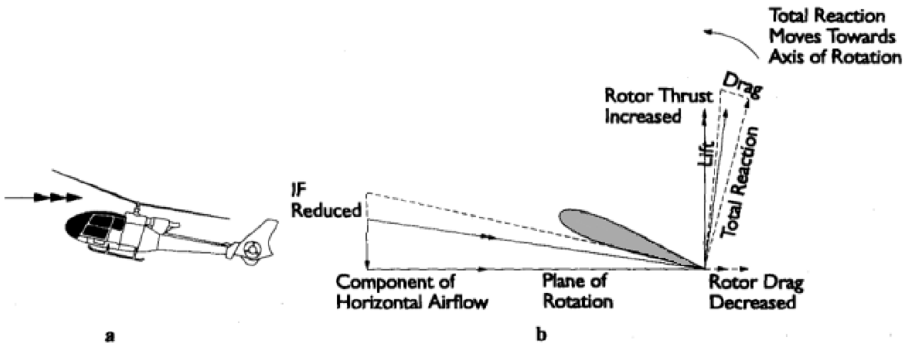


Fig 16 Change in Relative Airflow

b. **Increase in Total Rotor Thrust.** Another effect of tilting the disc back whilst the helicopter is moving forward is to change the airflow relative to the disc, Fig 16. As was explained in paragraph 19, translational lift, a component of the horizontal airflow (due to the forward movement of the helicopter) is passing through the disc at right angles to the plane of rotation, opposing the induced flow. The result is an increase in total rotor thrust. To prevent a climb the collective lever must be lowered.

c. **Increase in Rotor RPM.** Unless power is reduced when collective pitch is reduced, the Rrpm will rise. They will also increase rapidly in the flare for two other reasons, conservation of angular momentum and reduction in rotor drag.

(1) **Conservation of Angular Momentum.** An increase in total rotor thrust causes the blades to cone up. The radius of the blades' CG from the shaft axis decreases and the rotational velocity will automatically rise.

(2) **Reduction in Rotor Drag.** Rotor drag is reduced in the flare because the total reaction moves towards the axis of rotation. This results from the changed direction of the relative airflow. The forward movement of the total reaction vector causes the rotor drag component to be reduced, Fig 16b.

As a result of the flare the speed reduces rapidly and the flare effects disappear. Collective pitch and power which had been reduced during the flare must be replaced and, in addition, more collective pitch and power must be used to replace the loss of translational lift caused by the speed reduction, otherwise the aircraft would sink. The cyclic stick must also be moved forward to level the aircraft and to prevent the helicopter moving backwards. The power changes necessary during the flare have an effect on the aircraft in the yawing plane. Therefore, yaw pedals must be used to maintain heading throughout.

Landing

25. If collective pitch is reduced slightly in a hover IGE, the helicopter will descend but settle at a height where ground effect has increased total rotor thrust to again equal all up weight. Therefore a progressive lowering of the collective lever is required to achieve a steady descent to touchdown. When the helicopter is close to the ground the tip vortices are larger and unstable causing variation in the thrust around the rotor disc and turbulence around the tail and makes control difficult. For this reason, and to help to prevent ground resonance, the helicopter is normally landed firmly to decrease the chance of drifting when touching down.

Symmetry and Dissymmetry of Rotor Thrust

26. **Symmetry of Rotor Thrust.** If a helicopter is stationary on the ground in still air conditions, rotor turning and some collective pitch applied, then the rotor thrust produced by each blade will be uniform. The speed of the relative airflow over each blade will be equal to the speed of rotation of the blade, and if a given section on each blade of a four-bladed rotor is considered, the vector showing the relative airflow will have the same value irrespective of the position of the blade during its 360° of travel, see Fig 17. As the velocity of this airflow is equal to the blade's speed of rotation, this airflow will be referred to as V_R.

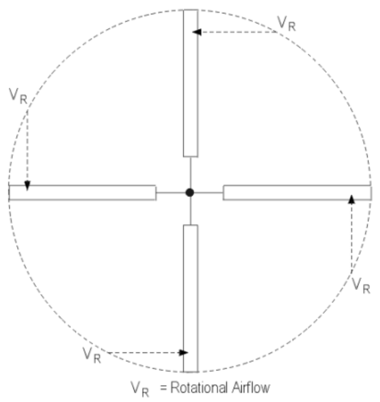


Fig 17 Relative Airflow - Still Air

27. **Dissymmetry of Rotor Thrust.** If the conditions change and the helicopter now faces into a wind, during the blade's rotation through 360° half the time it will be moving into wind and the remainder of the time it will be moving with the wind. The disc can therefore be divided in half, one half being the advancing side and the other the retreating side, see Fig 18.

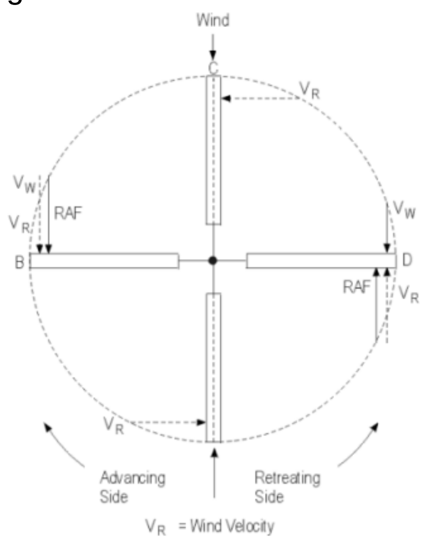


Fig 18 Relative Airflow - Wind Conditions

When the blade is at right angles facing into wind (position B), the velocity of the relative airflow will be a maximum and if the value of the wind speed is referred to as V_W, then at position B the velocity of the relative airflow will be $V_R + V_W$. As the blade continues to rotate, the effect of V_W will decrease and when the blade reaches position D the velocity of the relative airflow will have become $V_R – V_W$. If no change has taken place in the blade's plane of rotation, the rotor thrust being produced by the advancing blade at position B will be greatest and, for the retreating blade at position D, least. The value of rotor thrust across the disc will no longer be uniform and unless some method is employed to provide equality, the helicopter will roll towards the retreating side. This condition, where one side of the disc produces more rotor thrust than the other, is known as dissymmetry of rotor thrust.

Flapback

28. To maintain control of the helicopter dissymmetry must be prevented; one method of doing this is to decrease the angle of attack of the advancing blade and increase the angle of attack of the retreating blade so that each blade again produces the same value of rotor thrust. With the fully articulated rotor head this change in angle of attack takes place automatically by flapping but, as a result, the disc attitude changes. The manner in which it changes and the reason why this change in attitude prevents dissymmetry can be seen by following the movement of a blade through 360° of travel.

29. Starting at position A of Fig 19, the blade starts to travel on the advancing side and the relative airflow will increase. Rotor thrust begins to increase and, because it is free to do so, the blade will begin to flap up about the flapping hinge. As the blade flaps up the angle of attack will begin to decrease, rotor thrust decreases and the blade will proceed to follow a path to maintain the same value of rotor thrust as it was producing before it began to flap up. The blade, in fact, is flapping to equality. The further round that the blade progresses on the advancing side, the greater will be the velocity of the relative airflow; therefore, to maintain a constant value of rotor thrust, the rate at which the blade is flapping will steadily increase, with the maximum rate of flapping and, therefore, minimum angle of attack occurring when the blade reaches position B. For the next 90° of travel the velocity of the relative airflow begins to decrease, so the rate of flapping will decrease. When the blade reaches position C, the relative airflow will have the same value as at position A, so the rate of flapping dies out completely but, because the blade has been rising all the time from position A, the blade will reach its highest position at C. The reverse will take place on the retreating side, with the blade having its maximum rate of flapping down and, therefore, its maximum angle of attack at position D, reaching its lowest position at A. In flapping to equality, the blade will have flapped away from the wind. This change of disc attitude, which has occurred without any control movement by the pilot, is known as flapback.

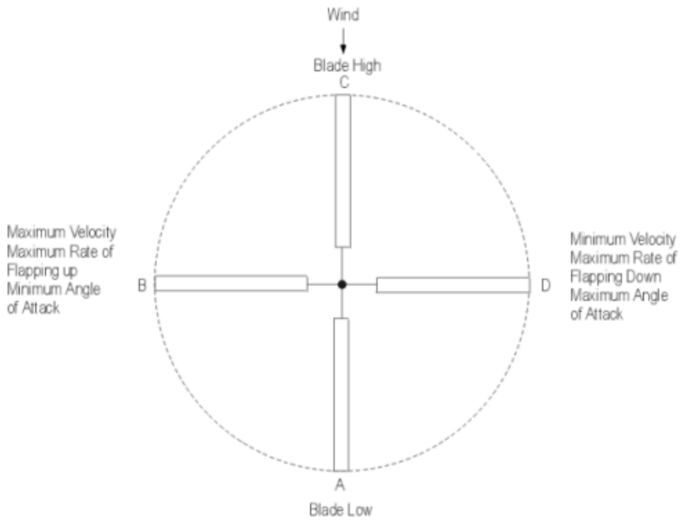


Fig 19 Disc Tilt Resulting from Blades Flapping to Equality

30. Figs 20a and b show that when the helicopter is on the ground and the disc is subject to wind, the disc attitude is altered, although no cyclic stick has been applied. The disc has flapped back relative to the wind and to the control orbit, and the blades are moving about their flapping hinges. However, the rotor thrust being produced will be the same value as before the disc flapped back, but tilted in direction.

31. If the pilot now moves the stick forward to return the disc to its original position (Fig 20c) it will be seen that the disc is now flapped back only in relation to the control orbit and not to the wind, and that movement is no longer taking place about the flapping hinges. Thus flapback has been counteracted by cyclic feathering, and, since the cyclic stick only changes the disc attitude, the value of the rotor thrust force remains unchanged. When the helicopter is airborne and moving in any horizontal direction, the effect will be the same as has been described for a helicopter on the ground facing into wind, with flapback being prevented by cyclic feathering. The first movement of the cyclic stick will tilt the disc to initiate horizontal flight, then a second movement will be necessary to prevent the disc from flapping back when the aircraft moves and gains speed. It should be noted however that some movement about the flapping hinges will still take place if the CG of the helicopter is not in the ideal position.

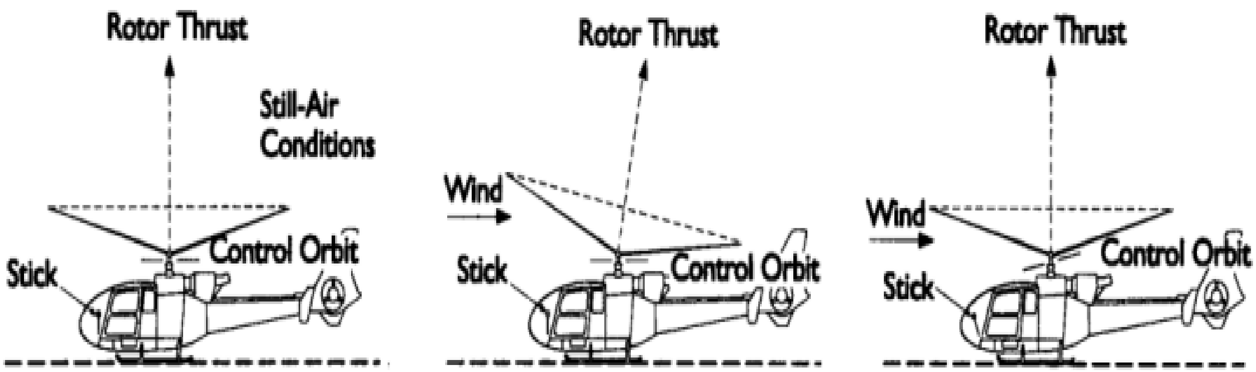


Fig 20 Relationship between Disc, Control Orbit and Stick Resulting from Flapback

Inflow Roll

32. The effect of moving air horizontally across the disc causes a reduction in the induced flow. However, this reduction is not uniform because air passing across the top of the disc is being continually pulled down by the action of the rotors. Thus air which is moving horizontally towards the disc will cause the greater reduction in induced flow at the front of the disc, and the smallest reduction at the rear of the disc, see Fig 21. The reduction in induced flow for the disc as a whole will produce an increase in rotor thrust but because the increase in the angle of attack is not uniform, it will also produce a change in the attitude of the disc. Assuming the flapback has been corrected, see Fig 22, the effect of a cyclic variation in angle of attack for a blade starting at position B, Fig 22b, must be considered.

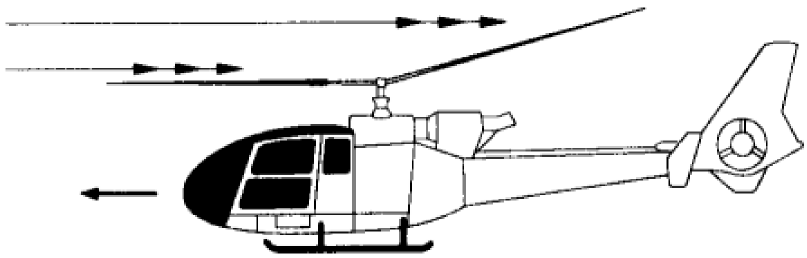


Fig 21 Relative Airflow at Front and Rear of Disc

As the blade moves towards position C, the increased angle of attack will cause the blade to flap to equality. The rate of flapping up will be a maximum as the blade passes position C because this is the point where there has been the greater reduction in induced flow. In the next 90° of travel the rate of flapping will slow down, dying out completely when the blade is at position D. Thus the blade will be rising all the time it is travelling from position B to reach its highest position at D. The reverse will take place for the next 180° of travel, with the blade having its maximum rate of flapping down at A and its lowest position at B. As a result of the inflow the disc will, therefore, tilt about axis AC towards the advancing side. The combined effect of inflow roll and flapback is, therefore, to tilt the disc about axis ZZ1, Fig 22c. As inflow roll will have its greatest effect at low speed, and flapback its greatest effect at high speed, the axis about which the disc will tilt will vary with forward speed. In general, the cyclic stick has to be positioned forward towards the retreating side to correct these effects in forward flight.

Factors Affecting Maximum Forward Speed

33. There are several factors which must be taken into account when trying to increase the maximum speed of a helicopter.

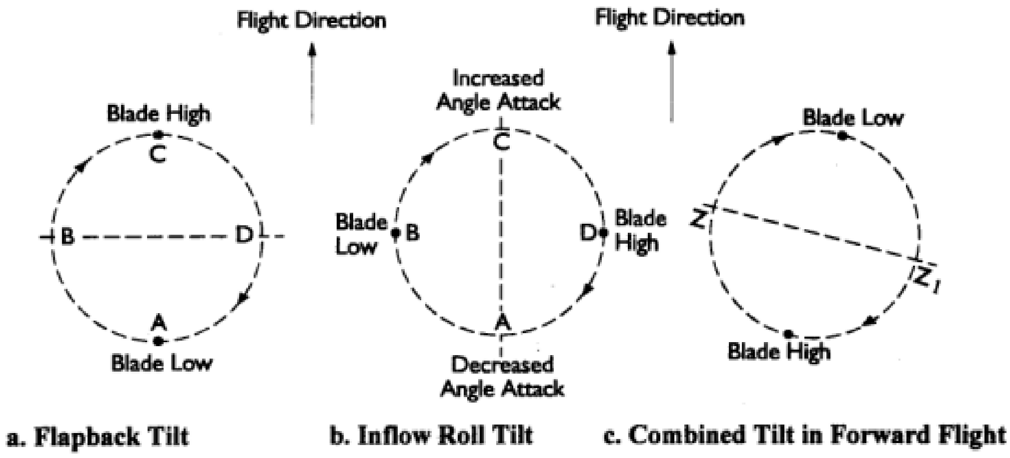


Fig 22 Combined Effect of Flapback and Inflow Roll

34. **Cyclic Control Limits.** To achieve forward flight the cyclic stick is moved to tilt the disc forward, the disc tilting by the same amount that the control orbit has been moved. As the airspeed increases the rotor disc flaps back relative to the cyclic control position and the attitude of the disc is maintained by moving the cyclic stick forward. There will be a speed at which the cyclic stick is fully forward and no further acceleration is possible. The amount of forward cyclic control is reduced if the helicopter's centre of gravity is aft.

35. **Power Available**. In level flight V_{MAX} is limited by power available. A higher speed may be possible in descent (Chap 6).

36. **Structural Strength**. As speed increases both the forces on the rotor and transmission and the levels of vibration increase. Apart from the limitation of the strength of the airframe and other components against these forces, the combination of stress and vibration causes fatigue. It is impractical to make components so strong that they do not suffer fatigue and, therefore, the level of vibration must be kept below that at which the failure of components may occur. This will set a limit to the maximum speed.

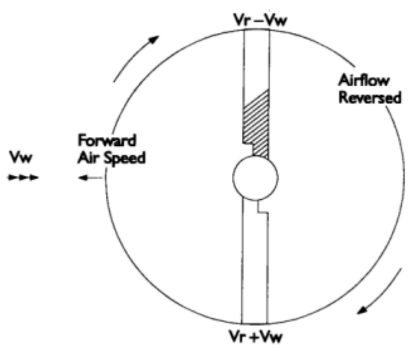


Fig 23 Airflow Reversal

37. **Airflow Reversal.** The speed of rotation of the retreating blade is high at the tip and low at the root, but the airflow from forward flight will have an equal value for the whole length of the blade and, where the airflow from forward flight is greater than the blade's rotational velocity, eg at the root end, the airflow will be from the trailing edge to the leading edge, causing a loss of rotor thrust. At higher airspeeds the airflow is reversed over a progressively large section of the blade leading to a greater loss of thrust, see Fig 23. The reduction of rotor thrust on the retreating blade by airflow reversal is countered by greater cyclic control and hence the retreating blade operates at an increasingly higher pitch angle and hence angle of attack.

38. **Retreating Blade Stall.** As the angle of attack of the retreating blade is steadily increased with increasing forward airspeed there will be a speed at which the airflow breaks away and the blade stalls. The large sudden loss of rotor thrust will cause the blade to flap down, but instead of flapping to equality the effect will be simply to stall the blade even further. The stall starts at the tip first and spreads inboard as shown in Fig 24.

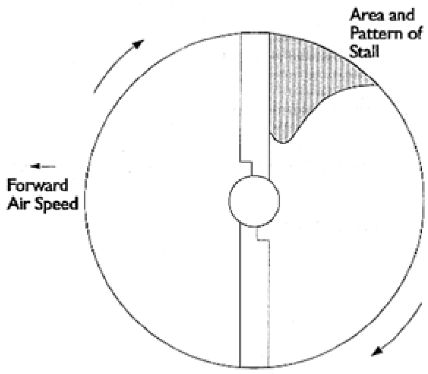


Fig 24 Retreating Blade Stall

The reason why the stall commences at the tip is shown in Fig 25. The variation in angle of attack along the blade will be offset to some extent by washout but in all conditions of forward flight the highest angle of attack will be at the tip.

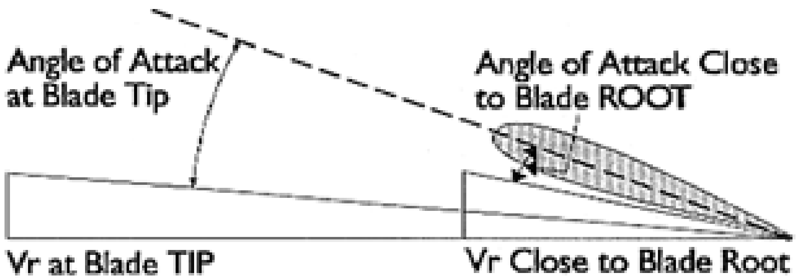


Fig 25 Stall at Tip Before Root

39. Characteristics of Retreating Blade Stall. The approach of the retreating blade stall can be detected by:

a. Rotor roughness.

b. Erratic stick forces.

c. Stick shake.

If these conditions are ignored, a pitch up tendency will develop followed by a roll to the retreating side. There will be a substantial loss of control and if the stall is severe, control may be lost completely.

40. Causes of Retreating Blade Stall. Retreating blade stall can occur as a result of:

a. High forward speed.

b. High G manoeuvres.

c. Rough, abrupt or excessive control movements

d. Flying in turbulent air.

A high all up weight/high density altitude will also aggravate the situation. Recovery action will depend upon which of the above in-flight conditions are prevailing when the stall symptoms are recognized. Recovery will normally be made by reducing forward speed, reducing collective pitch, reducing the severity of the manoeuvre or by a combination of these recovery actions.

41. **Compressibility.** As an example, the speed of rotation of the tip of a Gazelle rotor blade is approximately 400Kt. In forward flight at 150 Kt the advancing blade tip has a relative velocity of 550Kt. The velocity of sound at sea level is 660Kt. Compressibility is therefore significant. The main effects of compressibility are:

a. A reduction in the lift/drag ratio, requiring more power for the same total rotor thrust.

b. An increase in the pitching moment on the aerofoil which is normally very small. This requires greater control forces and leads to vibration.

c. The production of shock waves which increase vibration and noise. The effects can be reduced by using a high speed aerofoil section or sweep back at the blade tips. Any such solutions have penalties at low speeds.

AUTOROTATION IN STILL AIR

Introduction

1. In powered flight the rotor drag is overcome with engine power but, when the engine fails or is deliberately disengaged from the rotor system, some other force must be used to maintain the rotor rpm. This is achieved by allowing the helicopter to descend and by lowering the collective lever fully so that the resultant airflow strikes the blades in such a manner that the airflow itself provides the driving force. When the helicopter is descending in this manner, the rate of descent becomes the power equivalent and the helicopter is said to be in a state of autorotation.

2. Although most autorotations are carried out with forward speed, the explanation as to why the blades continue to turn when in rotation can best be seen if it is considered that the helicopter is autorotating vertically downwards in still air. Under these conditions, if the various forces involved are calculated for one blade, the calculations will be valid for all the other blades irrespective of where the blade is positioned in its 360° of travel. The various airflows and angles which will be referred to are shown in Fig 1.

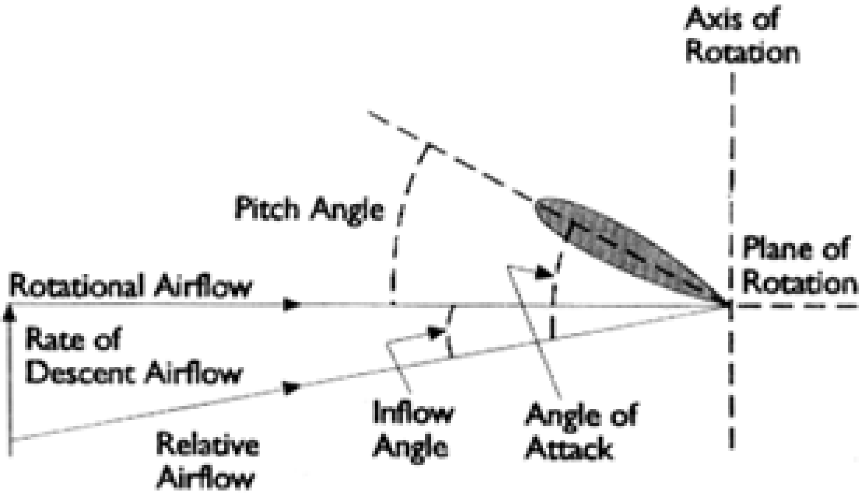


Fig 1 Autorotation - Terms Used

3. It will be noted that the inflow has been determined from the blades' rotational velocity and the airflow arising from rate of descent. This is not strictly true as the action of the blades slows down the rate of descent airflow, producing, in effect, an induced flow, making the inflow angle smaller than has been shown in Fig 1; the fact that it is smaller and how this affects the blade is considered later.

Autorotative Force/Rotor Drag

4. Consider three sections A, B and C of a rotor blade (Fig 2). The direction of the relative airflow for each section can be determined from the rotational velocity and the helicopter's rate of descent. The rate of descent will have a common value for each section but the rotational velocity will decrease from the tip towards the root. Comparing sections A, B and C, the inflow angle must therefore be progressively increasing (Fig 3). Because of the wash-out incorporated in the blade, the pitch angle is also increasing and as the blade's angle of attack is the pitch angle plus the inflow angle, the blade's maximum angle of attack will be at the root.

5. If the angle of attack for each section of the blade is known, the lift/drag ratio for these angles of attack can be ascertained by referring to the aerofoil data tables, and, by adding lift and drag vectors in the correct ratio, the position of the total reaction can be determined (Fig 3). Relating total reaction position to the axis of rotation (see Fig 3b) at section A, the total reaction lies behind the axis; at section B it is on the axis and at section C it is in front of the axis. Having determined the position of the total reaction, it can now be considered in terms of rotor thrust and rotor drag (Fig 3b). At section A, the condition is the same as in powered flight and the component of total reaction in the plane of rotation opposes rotation and is continually trying to decelerate the blade. At section B no part of the total reaction is acting in the plane of rotation and it is all rotor thrust; at section C the component of total reaction in the plane of rotation assists rotation and is continually trying to accelerate the blade. Under these conditions it is no longer referred to as rotor drag, but as the autorotative force.

6. Considering the blade as a whole, the section producing an autorotative force will be accelerating the blade, whilst the section producing rotor drag will endeavour to slow it down. To maintain a constant rotor rpm, the autorotative section must be sufficient to balance the rotor drag section of the blade, plus the drag set up by the ancillary equipment, tail rotor shaft and tail rotor, all of which continue to function in autorotation.

7. In normal conditions with the lever lowered, the blade geometry is such that the autorotative rpm are in the correct operating range, provided an adequate rate of descent exists. If the lever is raised during autorotation the pitch angles increase on all sections (Figs 2 and 3). Section B will tend towards section A and section C will tend towards B, thus the autorotative section moves outwards. However, section D at the root becomes stalled and the extra drag generated causes a decrease in the size of the autorotative section and therefore rpm decreases, stabilizing at a lower figure. This continues with further raising of the lever until such time as the blade is no longer able to autorotate.

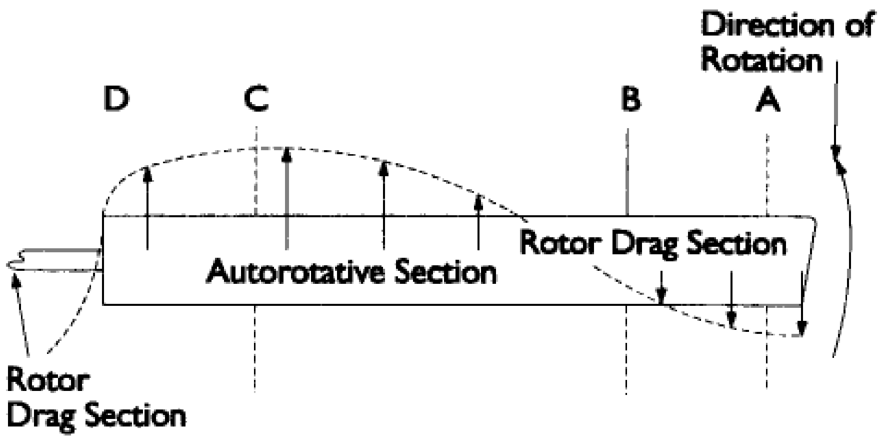


Fig 2 Distribution of Rotational Forces

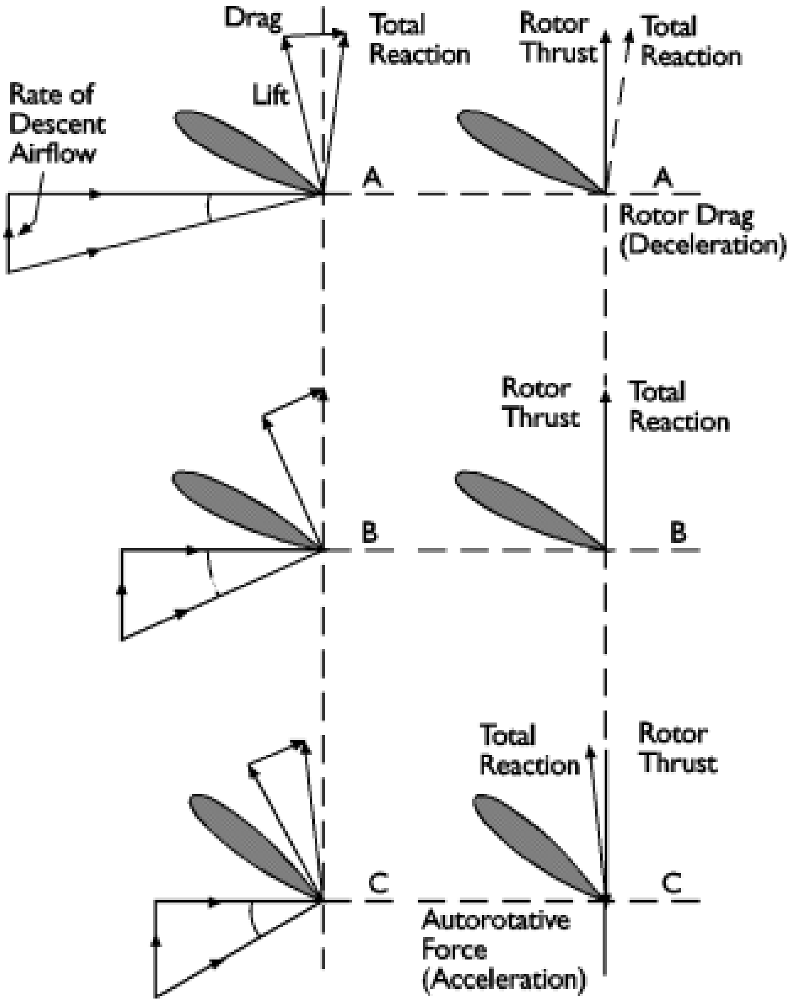


Fig 3 Autorotation - Position of Total Reaction and Autorotative Forces

8. Autorotative descent from high altitudes or at a high all-up weight leads to high rates of descent. Inflow angles will be higher and autorotative sections will be further outboard on the blades; rpm will be higher in autorotation under these conditions. It should be noted, however, that descent into more dense air decreases rate of descent and rpm for a constant lever position.

Rate of Descent

9. If the engine fails during a hover in still air and the collective pitch is reduced, the helicopter will accelerate downwards until such time as the angle of attack is producing a total reaction to give an autorotative force to maintain the required rotor rpm and a rotor thrust equal to the weight. When this condition has been established, the acceleration will stop and the helicopter will continue downwards at a steady rate of descent. If some outside influence causes the angle of attack to increase, there will be an automatic reduction in the rate of descent, the reverse taking place if the angle of attack is decreased.

10. Compared with a vertical autorotation in still air, the rate of descent will initially decrease with forward speed, but beyond a certain speed the rate of descent will start to increase again. The cause of this variation of rate of descent with forward speed is the changing direction of the relative airflow which occurs throughout the speed range in autorotation.

Relative Airflow - Vertical Autorotation

11. Consider a helicopter of a given weight requiring a mean angle of attack of 8° to provide the required rotor thrust and autorotative forces to maintain it in a vertical autorotation, and assume that this angle of attack is obtained when the rate of descent is 2,000 fpm. If the inflow angle is determined from rate of descent and a mean rotational velocity, it will be found to have a value of, say 10° (Fig 4a) but because the action of the blades slows down the airflow coming from below the disc, the actual inflow angle will be less, say, only 6° (Fig 4b). If the mean pitch value of the blade is 2°, then the angle of attack will be 8°, which is the angle required. So 2,000 fpm rate of descent is required by this particular helicopter to produce an inflow angle of 6°.

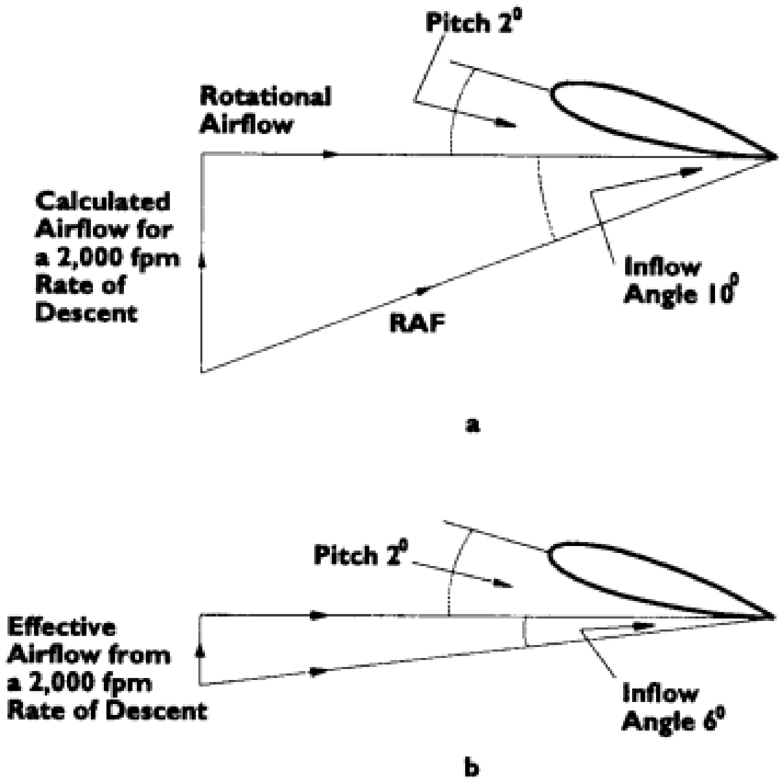


Fig 4 Inflow Angle and Rate of Descent Relationship

AUTOROTATION WITH FORWARD SPEED

Relative Airflow - Forward Autorotation

12. In determining the direction of the relative airflow when the helicopter is in a forward autorotation, three factors must be taken into account. The effect of these factors on the inflow angle will first be considered individually and then collectively.

13. **Individual Effect**

a. **Factor A.** To achieve forward autorotation the disc must be tilted forward. If the effective airflow from rate of descent (Fig 4) remains unchanged then the inflow angle must decrease (Fig 5). The angle of attack and therefore the rotor thrust must also decrease, causing an increased rate of descent.

b. **Factor B.** When the helicopter is moving forward, the disc will be subjected to not only the descent airflow, but also to a horizontal airflow. Because the disc is tilted to this horizontal airflow, it will further reduce the inflow angle (Fig 6). The angle of attack is further decreased therefore, causing an increased rate of descent.

c. **Factor C**. When the helicopter moves forward, the disc is moving into air which has not been slowed down by the action of the blades to the same extent as it is when the helicopter is descending vertically, therefore the effective rate of descent airflow will increase, which will result in the inflow angle increasing (Fig 7). The angle of attack and rotor thrust increases, giving a decreased rate of descent.

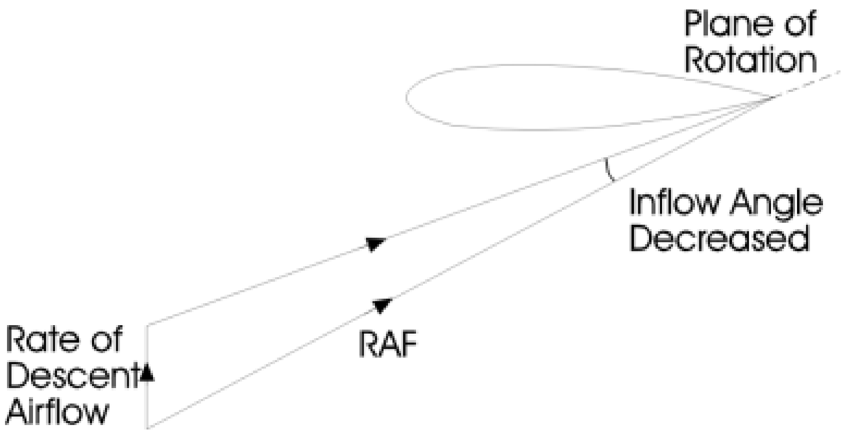


Fig 5 Inflow Angle - Disc Tilted Forward

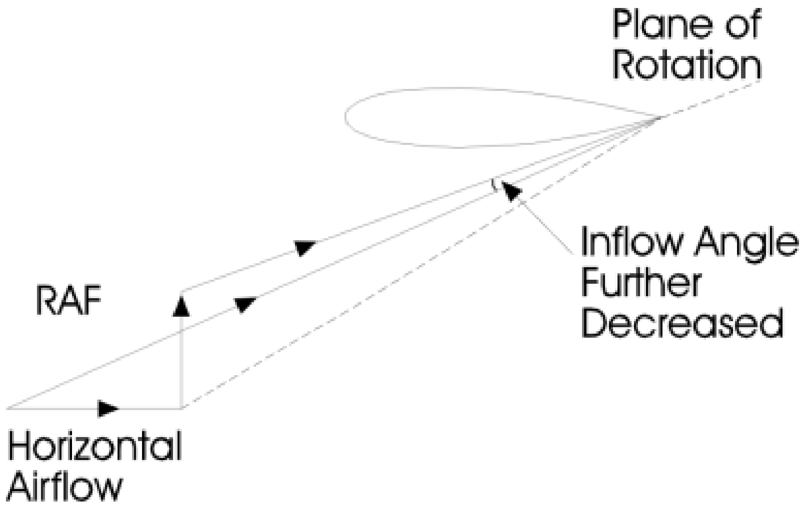


Fig 6 Inflow Angle - Effect of Horizontal Airflow

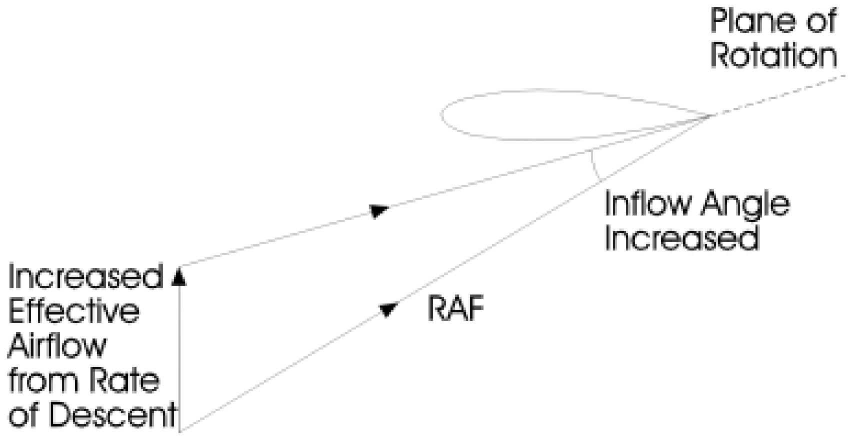


Fig 7 Inflow Angle - Effect of Forward Speed

14. **Combined Effect**. At low forward speed only a small tilt of the disc is required and the effect of factor C will be greater than the combined effects of factors A and B, so the inflow angle will increase. Angle of attack, and therefore rotor thrust, will increase and the rate of descent will decrease. As the rate of descent reduces, the inflow angle will decrease and the rate of descent will stabilize again when the angle of attack is such that the value of rotor thrust equals the weight. As forward speed is progressively increased, the effect of factor C will continue to increase the inflow angle, but, similar to the induced flow in powered level flight, its effect is large initially but diminishes with increasing forward speed. Since the disc has to be tilted more and more to overcome the rising parasite drag from the fuselage, the combined effects of factors A and B rapidly increase with forward speed. Therefore, a forward speed is eventually reached where the combined effects of factors A and B equal C and balance out. When this occurs the helicopter will be flying at the speed to give minimum rate of descent. Beyond this speed the effects of factors A and B will be greater than factor C, inflow angle will therefore reduce and the required rotor thrust can only be obtained from a higher rate of descent.

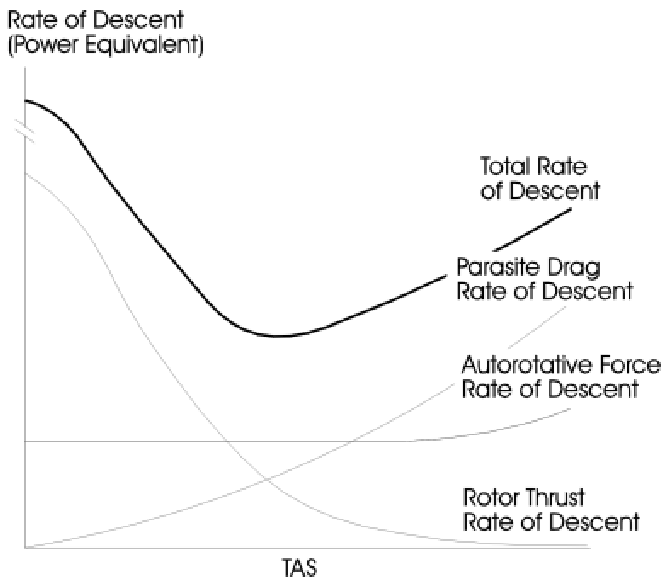


Fig 8 Effect of Forward Speed on Rate of Descent

Rate of Descent Requirements in Autorotation

15. In autorotation, a rate of descent will be required to:

a. Produce a rotor thrust equal to the weight.

b. Provide an autorotative force for the selected rotor rpm.

c. Produce a thrust component equal to parasite drag.

If these three components are plotted against forward speed, the graph would be similar to the one showing the power requirements for level flight (Fig 8).

Autorotation for Endurance and Range in Still Air

16. Autorotating to give the maximum time in the air must be at the speed to give the minimum rate of descent. The speed for endurance will therefore correspond to the lowest part on the rate of descent curve (Fig 9). Maximum range will be achieved when the helicopter is descending along its shallowest flight path. This will be achieved when flying at the best forward speed/rate of descent ratio. Relating this to the rate of descent curve, the optimum ratio will be at the speed where a line drawn from the point of origin of the graph is tangential to the rate of descent curve. For both range and endurance, rotor rpm should be as quoted in the Aircrew Manual.

Flare

17. The flare effect in autorotation will be exactly the same as for a flare in powered flight. Rotor rpm will rise because the increased inflow angle will cause the autorotative section to move further out towards the tip, and increased rotor thrust will reduce the rate of descent while flare effects last.

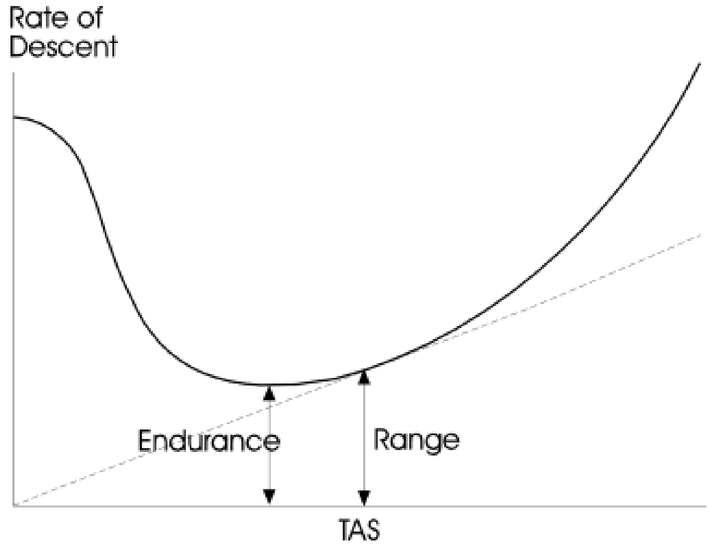


Fig 9 Range and Endurance

Avoid Area for Autorotation

18. To establish fully developed autorotation, following power failure, it is vital to lower the lever immediately, probably fully depending on forward speed and how quickly the lever is lowered after power loss is detected. At low forward speed it may also be necessary to gain forward speed. Lowering the lever and gaining forward speed will require considerable height loss before full autorotation is established at a safe speed to execute an engine off landing. If power failure occurs above optimum autorotation speed, flare may be used to recover Nr and reduce height loss as autorotation is established. At high airspeed and low level there may be insufficient time to reduce speed for a safe landing, despite the use of the lever and flare to maintain Nr and reduce height loss as autorotation is established. Avoid areas, determined by test flying, are published in the relevant aircraft Aircrew Manual; Fig 10 shows an example. Power failure when operating inside the avoid areas may result in an unsuccessful engine off landing as the aircraft may be too low and too slow, or too low and too fast, to establish full autorotation at a safe speed for landing. Operation within the avoid areas should be kept to a minimum. The relevant Aircrew manual should be consulted for specific techniques following power failure.

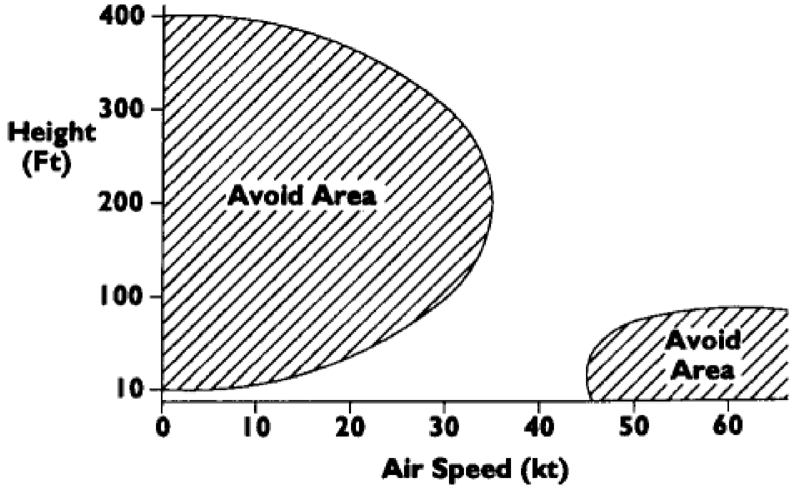


Fig 10 Typical Autorotation Avoid Areas

19. **Autorotative Landing**. When engine failure occurs at height, the aircraft has potential energy to dissipate and this is converted into kinetic energy during the descent process in autorotation. When near the ground, the kinetic energy stored in the rotor by virtue of its rpm is converted into work, in the form of a large increase in rotor thrust, by use of the collective lever, with a consequent rapid decay in Rrpm as the kinetic energy is used.

TOPIC- 4 : SUPERSONIC AERODYNAMICS

TRANSONIC AND SUPERSONIC AERODYNAMICS

Introduction

01. Aircraft flying at speeds well below the speed of sound send out pressure disturbances, or waves, in all direction. This enables an approaching aircraft to be heard and, more important for the aircraft, the air is warned of its approach. This warning gives the air time to divide and allows the passage of the aircraft with minimum disturbance.

02. If air was incompressible, the speed at which pressure disturbances travelled would be infinite, therefore, the disturbance created by an aircraft would be left everywhere instantaneously, regardless of the aircraft's speed; also the flow pattern around the aircraft would be independent of its speed. However, air is compressible and a change of density and temperature accompanies a change of pressure. Because of this, the speed of propagation of the pressure wave has a finite value the speed of sound.

03. As the speed of an aircraft is increased, there is a decrease in the distance ahead of the influence of the advancing pressure waves; there is also a change in the flow and pressure patterns around the aircraft and this will ultimately change its maneuverability, stability and control characteristics. To understands the changes in these patterns it is helpful to examine the changes that take place when a source of small pressure waves is moved through the air. The distinguishing feature of small pressure waves is that they travel at the same speed as they radiate from their source. Sound waves are audible pressure waves and, of course, travel at the speed of sound.

Definitions

04. **Speed of Sound (A).** The speed at which a very small pressure disturbance travels in a fluid under specified conditions is the speed of sound. The actual speed of a sound wave depends on the intensity of the pressure disturbance which constitutes the wave. In three dimensions, such a disturbance is propagated in the form of a spherical wave. In a standard atmosphere, the speed of sound is 1118ft/sec or 662 knots.

05. **Mach Number (M).** The relationship between true air speed and the speed of sound is known as Mach Number.

$$M_{FS} = \frac{V}{a} = \frac{\text{TAS}}{\text{Speed of sound}}$$

a. **Free Stream Mach Number (M_{FS}).** This is the mach number of the free stream flow sufficiently away from an aircraft (Unaffected air flow).

$$M_{FS} = \frac{V\ (\text{TAS})}{a}$$

M_{FS} is sometimes called Flight Mach Number.

b. **Local Mach Number (M_L).** When an aircraft flies at a certain M_{FS} the flow is accelerated in some places and slowed down in others. The speed of sound also changes because the temperature around the aircraft change.

Hence,

$$M_L = \frac{\text{Speed of flow at a point}}{\text{Speed of sound at the same point.}}$$

M_L May be higher, the same as, or lower than M_{FS}

c. **Critical Mach Number (MCRIT).** As MFS increases, so do some of the local Mach numbers. That MFS at which any ML has reached unity is called the critical Mach number. As will be seen later, MCRIT for an aircraft or wing varies with angle of attack; it also marks the lower limit of a speed band wherein ML may be either subsonic or supersonic. This band is known as the transonic range.

d. **Detachment Mach Number (M_{DET}).** If the leading edge of an aerofoil has no leading edge radius, there will be a M_{FS} at which the bow shockwave attaches to the sharp leading edge. This value of M_{FS} is M_{DET}. When this happens all values of M_L are supersonic except in the lower part of the boundary layer. In practice this rarely happens since wings have a significant radius to the leading edge, and behind the shock immediately in front of the leading edge there will be a small area of subsonic flow. Nevertheless M_{DET} can still usefully be defined as that M_{FS} above which there is only a small movement of the bow shockwave with an increase in speed. M_{DET} can therefore, be used to indicate the upper limit of the transonic range.

e. **Critical Drag Rise Mach Number (M_{CDR}).** M_{CDR} is that M_{FS} at which, because of shockwaves, the CD for a given angle of attack has increased significantly. Different criteria are often used, ie 0.002 rise in CD, 20% rise in CD.

06. Critical Mach Number and Critical Drag Rise Mach Number depend on the design of the aerofoil. Their values also vary with angle of attack.

07. **Definitions of Flow.** Flow speed is divided into different speed bands as illustrated in Fig-01

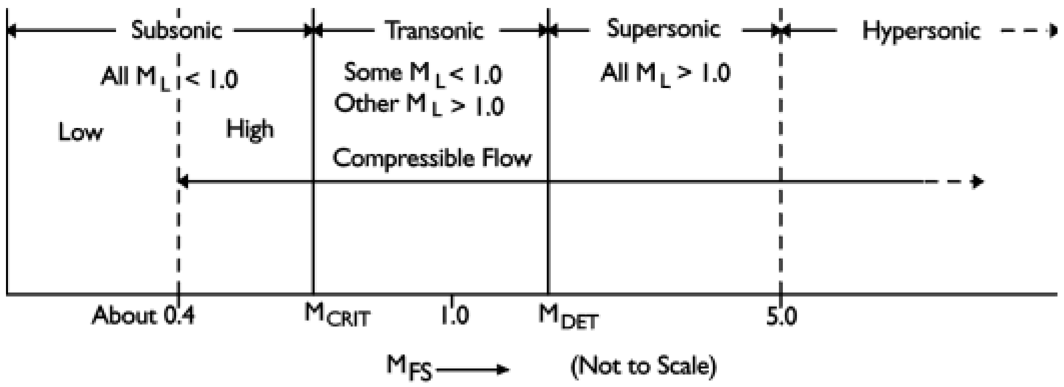


Fig-01 - Flow Speed Ranges

NOTE:

1. The subsonic region has been subdivided at M = 0.4 since below this Mach number errors in dynamic pressure, assuming incompressibility, are small. However, compressibility effects can be present even at M = 0.4; whether they are or not depends on wing section and angle of attack.

2. The actual values of M_{CRIT} and M_{DET} depend on individual aircraft and angle of attack.

3. A third definition of the transonic range is: that range M_{FS} during which shockwaves form and move significantly.

08. **Incompressible Flow**. Flow is treated as incompressible (density constant) when its Mach Number is equal to or less than 0.4. At low airspeeds, air suffers only small pressure changes, which cause a negligible change in density.

09. **High Speed Subsonic Flow.** This band covers all flows for which the speed is high enough (0.4 Mach) to give rise to significant compressibility effects. Local velocity is everywhere less in air density as velocities approach that of sound and the effects of this on the flight characteristics of an aircraft.

10. **Transonic Flow**. This band exists between M_{CRIT} and M_{DET}.This can be defined as that band of Free Stream Mach Number during which shock waves form and mover significantly. It is also defined as such flows in which there are some regions of subsonic and some of supersonic flow. But the Free Stream remains subsonic.

11. **Supersonic Flow.** Fully developed supersonic flow consists of a flow in which the local speed is everywhere greater than the local speed of sound. This flow is called Hypersonic Flow.

Propagation of a Sound Wave

12. The two properties of air which determine the speed of sound within it are resilience and density. Resilience describes how readily the air regains its original state having been disturbed. If one leg of a vibrating tuning fork is considered as the leg moves sideways, the air adjacent to it is compressed and the molecules are crowded together. The air, recovering from its compression, expands and compresses the air adjacent to it and so a pressure wave is propagated.

13. As each particle of air is compressed, the individual speed of the crowded molecules is increased and this affects the expansion and compression of the particles surrounding it. The more the air that can be compressed, the higher will be the increased speed of the molecules, the more rapid will be the expansion and so the faster the wave will travel. Temperature is a measure of molecular speed, and therefore increasing molecular speed suggests a rise in temperature in the air. However, this is not so because the situation is adiabatic, ie there is no overall rise in temperature and the temperature change in the production of small pressure waves is infinitesimal. But if the temperature of the air is increased as a whole, then the added increase in molecular speed as the air is compressed is sufficient to cause an increase in the rate of expansion, and therefore an increase in the speed of propagation of the pressure wave, ie the speed of sound has been increased by an increase in temperature.

14. In terms of pressure and density, a2 = p/ ρ where γ is the ratio of the specific heats (SH) SH constant pressure/SH constant volume= 1.4 for air. This can be rewritten as a2 = RT where R is the gas constant and T is in °K; therefore a = √ RT . Allowing for the two constant, it can be seen that
a α √T.

15. It should be noted that, in the transmission of pressure waves, air is not physically displaced, it merely vibrates about a mean position as does the prong of a tuning fork. The wave motion can be seen from a graph showing pressure variations against distance from a source at an instance of time (Fig-02).

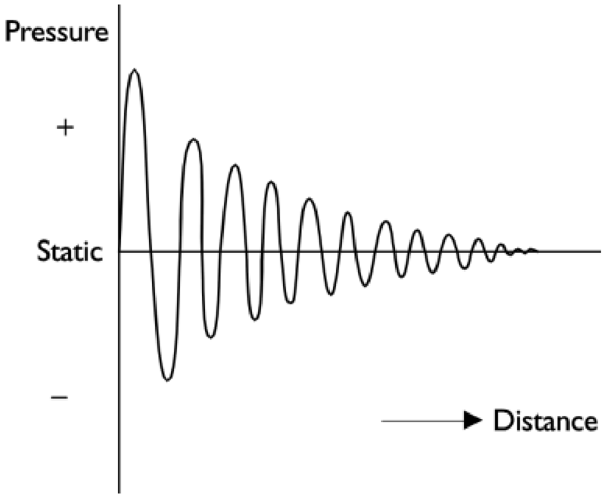


Fig- 02 Pressure Waves from a Stationary Source

16. The size of the wave is measured by its amplitude, ie the maximum change of pressure from static. The amplitude of a sound-wave is approximately one millionth of an atmosphere. In free air the waves weaken with distance from source because the energy in the wave is spread over an ever-increasing surface. The amplitude decreases rapidly at first, and then more gradually until the wave becomes too weak to measure.

Pressure Waves from a Moving Source

17. **Source Moving at Subsonic Speed.** Fig- 03 shows the pattern produced at a given instant in time. The sound-waves emanate in all directions relative to the source, although they are closer together ahead of the source than behind it. The waves maintain their separation and there is no tendency for them to bunch.

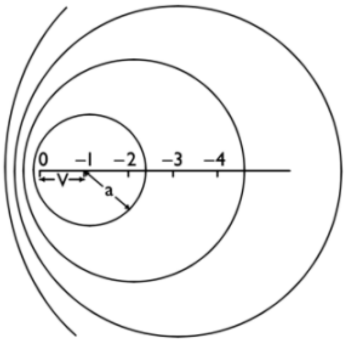


Fig - 03 Pattern from a Subsonic Source

18. **<u>Source Moving at Sonic Speed</u>**. A different pattern is produced when the source is moving at the speed of sound (Fig - 0 4).The waves cannot move ahead of the source; they bunch up and form a Mach wave ahead of which the air is quite unaware of the existence of the sound source. The Mach wave is not a shockwave, it is merely a line dividing areas where the source can be heard and areas where it cannot. As the Mach wave is at right angles to the direction of movement of the source the wave is called a normal Mach wave.

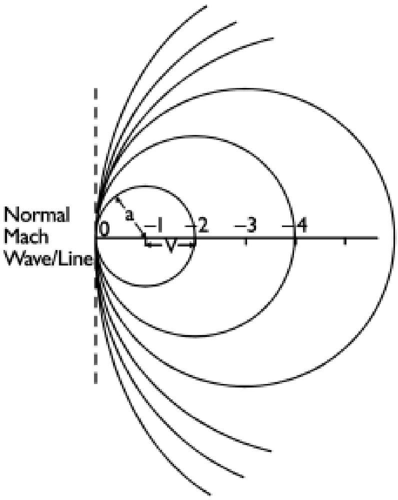


Fig 4 Pattern from a Sonic Source

19. **<u>Source Moving at Supersonic Speed.</u>** At supersonic speeds yet another pattern is produced (Fig -05), again with a boundary beyond which no wave can pass, ie the limit of influence of the source. This boundary is called an oblique Mach wave and the angle it makes with the flight path is called the Mach angle (m). From Fig -05 it can be seen in triangle AOB that sin m = a/V, but as M = V/a (para 5), sin m = 1/M In the air this pattern is three-dimensional so the boundary becomes a surface called the Mach cone. To distinguish between the regions where the air is affected by the source and where it is not, the terms Mach after-cone and Mach fore-cone respectively are used.

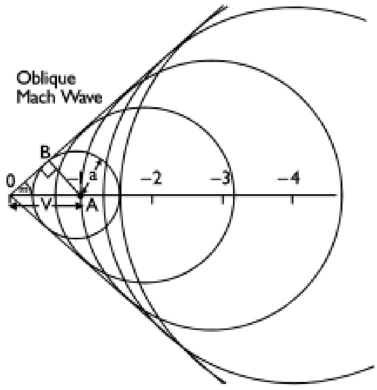


Fig- 05 Pattern from a Supersonic Source

20. **Mach Waves.** It should be noted that a flow passing through a Mach wave is affected infinitesimally since the pressure change across the wave is infinitely small. A Mach wave, or line , is a line along which a pressure disturbance is felt and the significance of Mach lines will be appreciated when expansions in supersonic flow are considered later.

21. **Large Pressure Waves.** It was stated that small pressure waves travel at uniform speed. When large pressure waves are produced (say, by a wing) there is a significant temperature increase at the source. This increase reduces with distance from the source and changes the speed of wave propagation as the waves radiate from the source. Due to this temperature rise, there is an increase in the local speed of sound and the initial speed of propagation of the pressure wave is at that higher sonic speed.

SHOCKWAVES

Formation of a Bow Shockwave

22. The pressure pattern from an aerofoil section at some subsonic speeds is well known. In particular, the region close to the leading edge will be experiencing pressure higher than atmospheric. Since the pressure and temperature are increased, then the speed of sound in that region will be higher than in the undisturbed flow some distance ahead of the wing. Using the same reasoning, by beginning at the leading edge where the pressure is highest, then moving up-stream ahead of the wing, pressure and temperature will reduce until finally a point is reached where they have reduced to the free stream static values. Between this point and the leading edge, the speed of sound will be higher than that of the free stream because of the compression and consequent temperature rise. The symbol conventionally given to this locally increased speed of sound is a'. If a typical curve of pressurization is plotted from its static value ahead of the leading edge, the result would be as shown in Fig - 06.

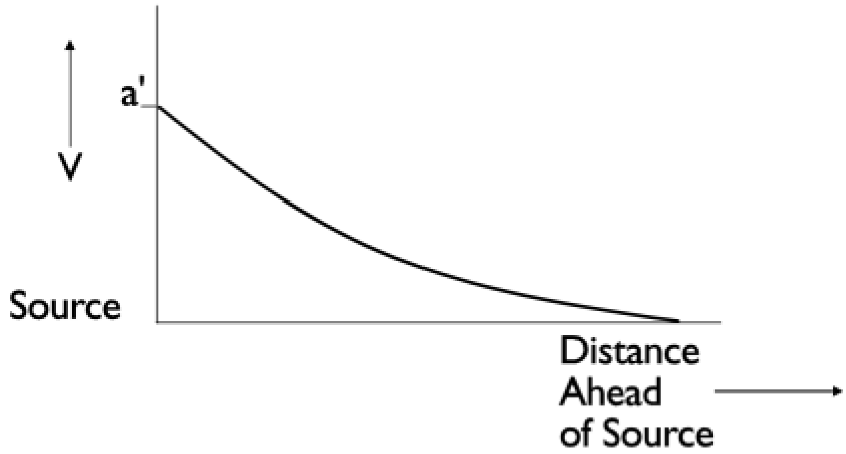


Fig - 06 Pressure Variation from a Static Source

23. When a wing or any object is placed in a flow, the flow around the object is deflected. If the deflection is such that the air is compressed, then the deflection and speed of the flow will determine the compression and temperature rise and, consequently, the local increase in the speed of sound. Consider an infinitely thin flat plate; if it is at 0° angle of attack, there will be no pressure changes round it. If it is set at a positive angle of attack, the pressure rise underneath will increase the temperature such that the increase in speed of propagation of the pressure waves ahead of the plate is a' (where a is the speed of sound in the undisturbed flow). The initial value of a' depends on the shape and speed of the source; the blunter the source, the greater the increase in the local speed of sound.

24. Considering now a wing at an MFS <1.0, the pressure disturbances from the wing will propagate forward initially at some value of a', which will decrease with distance until its value is equal to a. Since the aircraft is subsonic, ie its speed is less than a, the disturbances will continue to progress up-stream until they finally die out; they will not bunch and no Mach wave will form. This is shown in Fig - 07.

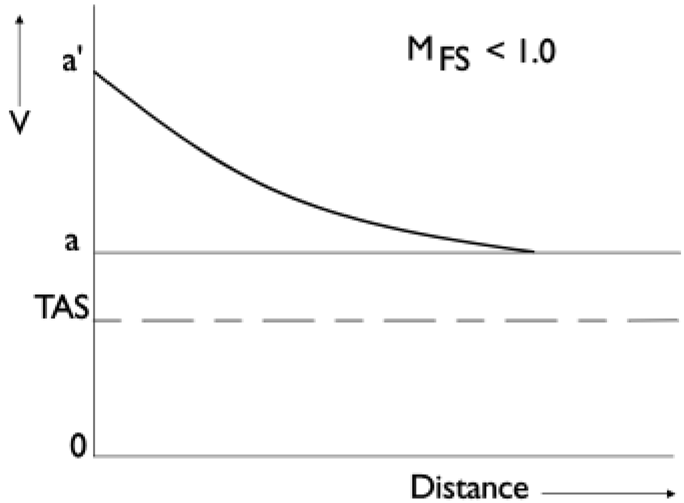


Fig - 07 Pressure Variation from a Subsonic Source

25. When M_{FS} = 1.0, the pressure waves propagate initially at a value of a' greater than M_{FS} resulting from the heated high pressure region ahead of the wing. They can, therefore, escape forward away from the advancing wing for as long as the temperature and pressure remain higher than ambient and P_0 (the free stream static pressure) respectively at which stage the disturbance cannot make any further progress up-stream. Thus, a Mach wave will form at this point well ahead of the aircraft and the blunter the wing leading edge (more disturbance) the further away it will be. The location of the Mach wave is shown on Fig - 08. Note that it is still a Mach wave - not a shock wave - because pressure is P_0 at this point.

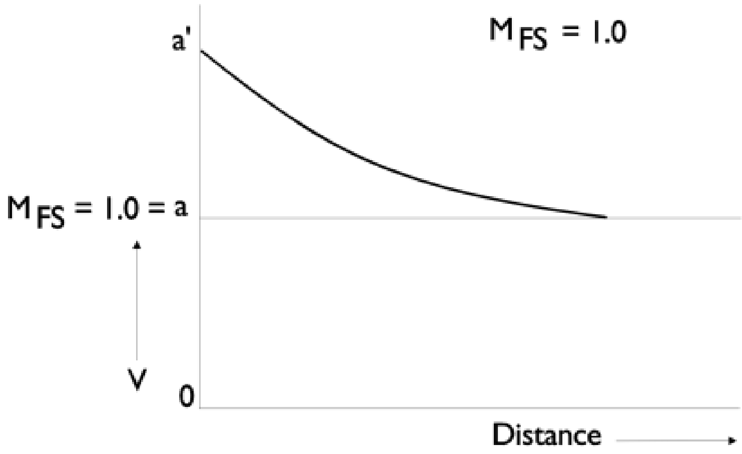


Fig - 08 Pressure Variation from a Source at the Speed of Sound

26. An increase in M_{FS} above M 1.0 results in an increase in the initial a¢, but at some distance ahead of the aircraft the reducing value of a' will equal the forward speed of the aircraft, ie a' will equal M_{FS}. The pressure waves will therefore be unable to penetrate further up-stream, as shown in Fig - 09. The pressure waves will bunch and form a shockwave called the bow shockwave; this wave is the forward limit of influence of the aeroplane; air ahead of it receives no warning of the aircraft’s approach.

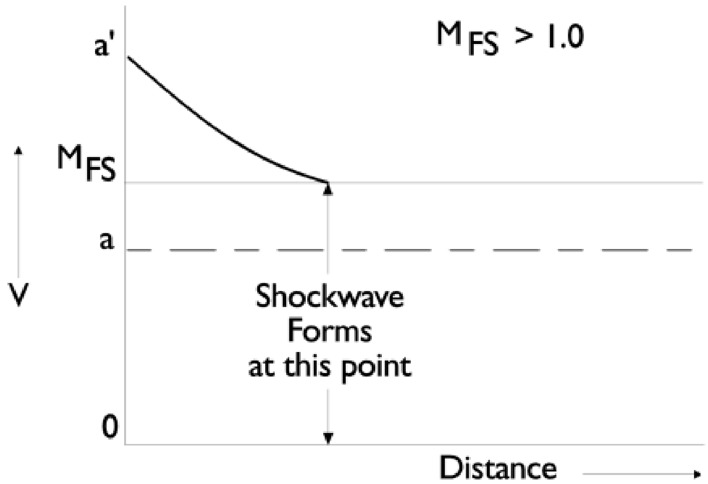


Fig - 09 Pressure Variation from a Supersonic Source

27. As far as an observer on the ground is concerned, there is no aircraft noise ahead of the bow shockwave, but as the shockwave passes the observer there is an intense increase in noise, the sonic "bang", and then the normal aircraft sound is heard. The second "bang" comes from the shockwave formed around the wings and fuselage of the aircraft and will be explained in a later paragraph.

28. If the aircraft continues to accelerate, the pressure waves reach their forward limit of travel even closer to the source. Once again the bow shockwave will be positioned where the decreasing a' is equal to the M_{FS} and will be more intense. Eventually, when the M_{FS} reaches the same value as the initial a' of the disturbance, the bow shockwave attaches to the leading edge; this is at the detachment Mach number (M_{FS}) and any further increase in speed results in the shockwave becoming more oblique. This stage will only be reached if the leading edge is very sharp, since the value of a' is a function of speed and shape, and increases with speed. Where there is a rounded leading edge, an increase in speed will give rise to increased stagnation temperatures and the shock will be "held off".

29. The disturbances which cause an aerofoil to generate shockwaves originate at the points where the airflow suddenly changes direction - notably at the leading and trailing edges. The angle through which the airflow changes direction at those points is known as the deflection angle. Below is a table of detachment Mach numbers for particular deflection angles with regard to the blow wave.

Deflection Angle	M_{DET}
10□	1.41
20□□	1.83
30□	2.00

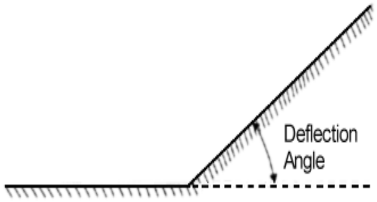


Fig – 10 Deflection Angle

30. Comparing the case V > a (small source) and V > a' (large source), it is found that because a' is greater than a, the wave angle (W) is always greater than the Mach angle (m), as shown in Fig - 11.

31. Also from Fig - 11, sin W = a'/V. Multiplying by a/a gives sin W = a'/a x a/V = a'/a x 1/M from which W can be calculated.

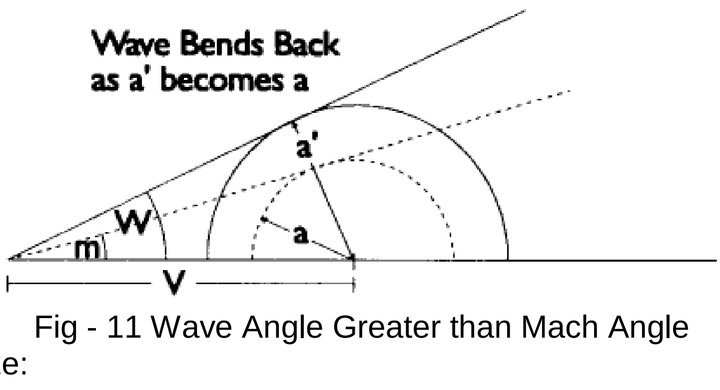


Fig - 11 Wave Angle Greater than Mach Angle

32. To summarize:

a. M_{FS} < 1.0 - no bow shockwave.
b. M_{FS} > 1.0 < a' - detached normal shockwave.
c. M_{FS} > a' - oblique attached shockwave.
d. The blunter the source, the higher M_{DET} will be.

Wing Surface Shockwaves

33. The bow shockwave is not the first shockwave to form. Long before the aircraft as a whole has reached Mach 1, some portions of the flow around the aircraft have exceeded the speed of sound. When the first local Mach number (M_L) equals 1.0 somewhere around the aerofoil, the aircraft has reached its critical Mach number (M_{CRIT}) and shockwaves will begin to form.

a. **Conditions for Shockwave Generation.** Fig 12a shows the local Mach numbers around a wing at a speed in excess of M_{CRIT} (M_{FS} = 0.8 in the example) at the instant in time before any shockwave has had time to develop. Where the top and bottom airflows meet at the trailing edge, they are deflected violently (each through a different deflection angle) to follow a common path. At the point where they meet there will be another region of high pressure similar to the region of high pressure at the leading edge. Beneath the wing, since the highest M_L = 0.95, the pressure waves travelling at sonic speed are able to escape forwards. Similarly, above the wing nearer the trailing edge, in the flow where M_L = 0.9 and 0.95, pressure waves can progress forwards but they are soon brought to rest at the point where M_L = 1.0.

b. **Top Shockwave**. Fig 12b shows the situation an instant later when only a top shockwave forms. Shockwave generation is complicated somewhat by the presence of the boundary layer, part of which must always be subsonic. This enables the pressure rise to be communicated forward of the shock, thickening the boundary layer and giving rise to a further compressive corner ahead of the main shockwave known as the lambda foot. This interaction between the shockwave and the boundary layer is dealt with in more detail in Design for High Speed Flight.

c. **Bottom Shockwave**. As M_{FS} is increased the top shockwave will grow steadily stronger and start to move rearwards, eventually attaching to the trailing edge. At some stage during this movement, some local Mach numbers below the wing will reach unity and a bottom shockwave will form (Fig 12c). This will be weaker than the top shockwave because a wing at a positive angle of attack will feature a smaller deflection angle for the bottom shockwave. This smaller deflection angle also means that the bottom shockwave will move rearwards faster than the top shockwave and will attach to the trailing edge before it (Fig 12d).

d. **Progression to M_{DET}**. As M_{FS} is increased further, both surface shockwaves become attached to the trailing edge (Fig 12e) and, as speed is increased even further, become more and more oblique. The bow wave forms once M_{FS} exceeds 1.0 and moves towards attachment but, for a blunt leading edge, does not quite achieve this stage as llustrated in Fig 12f. Conversely, the sharper the leading edge the sooner will the weaker shockwave become attached (at M_{DET}) and any further increase in Mach number will cause the normal shockwave to become oblique.

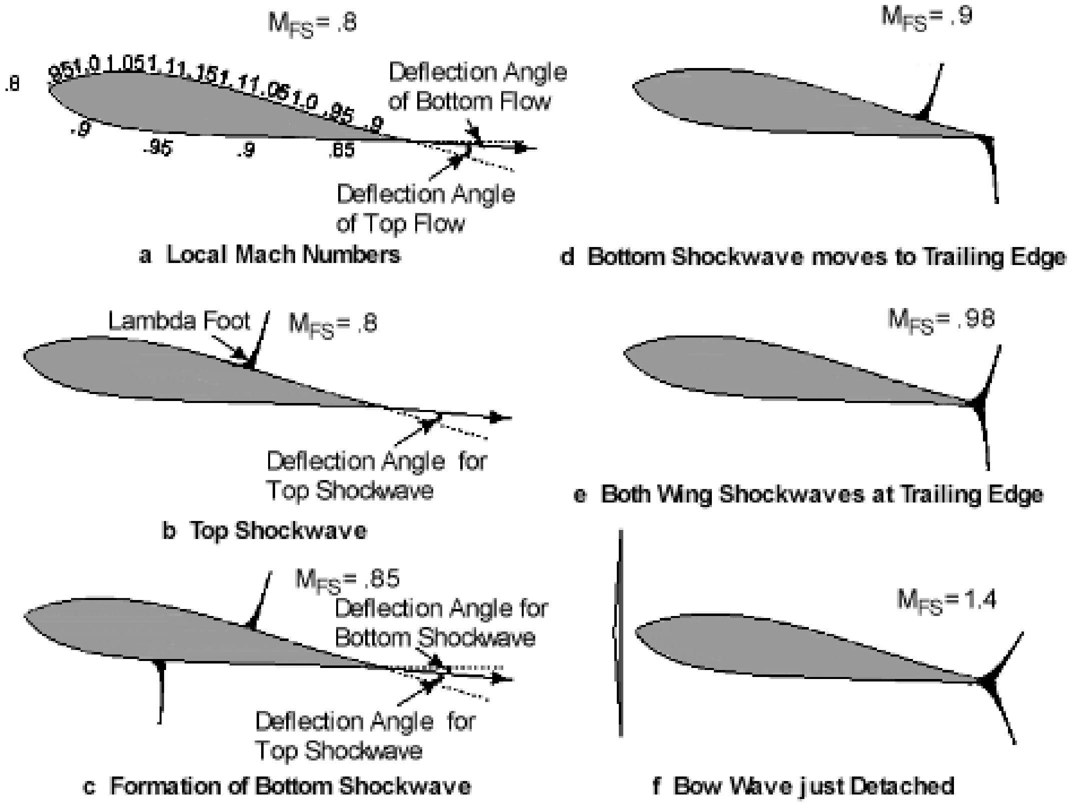


Fig 12 The Formation of Wing Shockwaves

<u>Acceleration of a Supersonic Flow</u>

34. To examine the changes that take place when supersonic flow is accelerated, consider the flow through a venturi tube, as in Fig 13. The up-stream end is connected to a reservoir containing air the total pressure P_0 and temperature T_0 of which are maintained constant. The down-stream end is connected to another tank in which the pressure may be varied. If no pressure difference exists along the duct there is no flow. If the pressure P is decreased slightly to P_1, then a low speed flow results, producing a pressure distribution as shown.

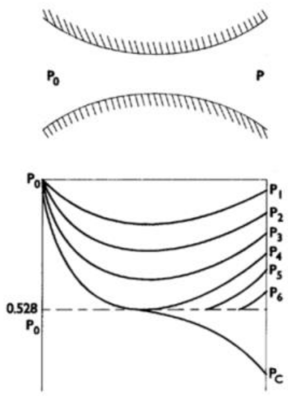


Fig 13 Supersonic Flow Acceleration in a Duct

Gradual lowering of the pressure P will lead to larger flow speeds until at pressure P_4 there is a throat pressure of 0.528Po and a flow speed of M = 1.0. If the pressure P is decreased even further to P_5, the change in pressure will be transmitted by a pressure wave which will travel at Mach 1.0 up-stream from the downstream end of the venturi. This can reach the throat but there it will meet the flow travelling downstream at the same speed and so it will be unable to pass through the throat. The flow up-stream of the throat will therefore be unaware of any changes in pressure downstream of the throat, and will remain unchanged no matter how large or small are further reductions in P. This produces several important results:

a. M = 1.0 is the highest Mach number that can be obtained at the throat.

b. At M = 1.0 the pressure will always be 52.8% of the total head pressure. (In this case THP is P_0 because the situation started with no flow.)

c. Maximum mass flow is obtained with M = 1.0 at the throat. The flow at the throat is sonic and so mass flow is independent of the down-stream pressure.

d. The streamlines are parallel at the throat.

35. The reduction in pressure is, however, felt up to the throat and the adverse pressure gradient is removed in a small section of the duct. Now a sonic flow is encountering diverging conditions in a cross-sectional area of no pressure gradient. What happens to the flow can be best explained by considering the small section of the duct which has just started to diverge from the throat.

36. Fig 14 shows a very small section of a venturi at, and just beyond, the throat through which there is a steady flow. A small, very thin disc of air lying between XX and YY travelling at sonic speed will be considered as it moves to the position X_1X_1 and Y_1Y_1. There is no pressure difference at the moment between A and B.

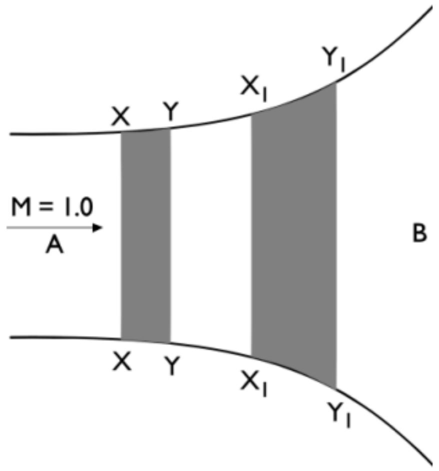


Fig 14 Supersonic Flow in a Divergent Duct

37. In seeing how velocity and Mach number will change, three separate stages are considered:

a. On moving out of the throat, because of inertia, the disc faces will want to maintain their velocity. The duct has, however, diverged and the disc will expand to fill the available space. In so doing the density, and with it the temperature, will decrease; this increases the Mach number.

b. In comparison with X_1X_1, the greater expansion, and therefore the greater density change, is felt at position Y_1Y_1. Thus there will be a pressure difference across the disc and the disc will accelerate. If the velocity increases, Mach number increases.

c. In a steady flow the mass flow is constant and the same number of discs will pass a point in unit time. However, the velocity has increased so there has been an apparent increase in mass flow. To keep the mass flow constant the thickness of the disc must increase and this means a further drop in density and temperature. As a result Mach number again increases.

NOTE:

1. Because of the density changes, a large increase in Mach number can be achieved for a relatively small increase in velocity.

2. The shape of the duct controls the expansion and thus the acceleration.

3. This effect could be produced in subsonic flow if conditions of no pressure gradient could be achieved from A to B. Thus we have sonic flow expanding and accelerating in conditions of divergency. Streamlines of the flow will also diverge.

38. Referring back to the whole venturi tube in Fig 13, a reduction of pressure to P_6 means that the area of no pressure gradient will be increased and the flow will be free to expand and accelerate along the curve to PC. This curve is the plot of flow if the speed is supersonic for the whole of the venturi's diverging length, and its shape is entirely dependent on the shape of the diverging part of the duct. (See para 37, note 2).

39. At some distance down the duct the now supersonic flow will encounter an adverse pressure gradient. The decreasing pressure of the expanding supersonic flow is equal to the pressure in the duct and the flow will be forced to decelerate. This deceleration takes place through a shockwave.

40. Considering a curved wing surface as part of a duct the important fact to appreciate is that the flow will be parallel to the surface and the change in surface ahead of the flow will be sensed as an area of divergence. When an M_L = 1.0 is reached the flow will be free to accelerate within the limits of the shape of the camber of wing and until it encounters no more divergence or a strong adverse pressure gradient.

41. The flow through a duct can be summarized as follows:

Flow	*Duct or Stream lines*	
	Divergent	*Convergent*
Subsonic	P ↑ρ↑V□↓	P ↓ρ↓V↑□
Supersonic	P ↓ρ↓V↑□	P ↑ρ↑V□↓

42. Flow through a duct has been considered but, to understand the reason behind the design of a fully supersonic wing section, it is necessary to examine in rather more detail how a supersonic flow negotiates sharp corners.

Expansive Corners

43. As its name implies, an expansive corner is a convex corner which allows the flow to expand and thus accelerate. Any corner can be considered to consist of a series of infinitely small changes in surface angle and Fig 15 shows a single corner broken down into a series of greatly exaggerated steps.

44. Consider the two streamlines in the supersonic flow M1 as they reach the corner. The one adjacent to the surface will sense the change in surface as soon as it gets to the corner, the flow will expand, accelerate and, associated with the decrease in density, the pressure will decrease. This pressure disturbance will be felt along a Mach line appropriate to the flow M_1. The streamline further away from the surface will be "unaware" of the corner until it reaches the Mach line originating at the corner. This Mach line is a boundary between relatively high and low pressure, therefore a pressure gradient is felt across it such that the streamline is accelerated slightly and turned through an angle equal to the change in surface angle. It now continues parallel to the new surface at a higher Mach number (V increased, a decreased because of lower temperature). The streamlines are now farther apart. The same process will be repeated at the next change in surface angle with one important difference: the Mach
angle of the flow M_2 will be smaller.

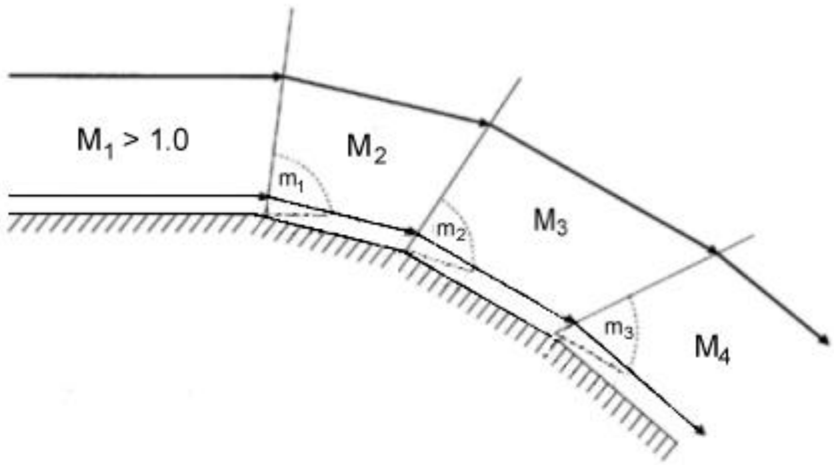


Fig 15 Supersonic Flow Round a Convex Corner

45. The process outlined above will take place at a corner through an infinite number of Mach lines and, because the lines "fan" out, the expansion and acceleration is smooth. The region within which the expansion takes place is limited by the Mach lines appropriate to the speed of the flow ahead and behind the corner; this is called a Prandtl-Meyer Expansion (Fig 16).

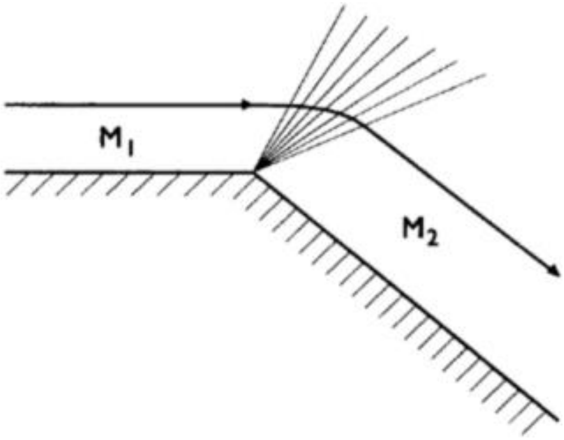


Fig 16 Prandtl-Meyer Expansion

46. The decrease in pressure, ie a favourable pressure gradient, round an expansive corner in supersonic flow allows an attached boundary layer to be maintained; this is exactly the opposite to what happens in a subsonic flow where an adverse pressure gradient would exist causing the boundary layer to thicken and break away. Consequently there is no objection to such corners on essentially supersonic aircraft and design features are permitted which would be quite unacceptable in subsonic aircraft.

47. An example of expansive corners and associated velocity and Mach number increases is given in Fig 17. The initial flow is Mach = 1.0 in standard conditions. The theoretical maximum angle of expansion for sonic flow is 130.5°. The vectors indicate true velocity of the flow. It should be noted that to increase the final speed the temperature of the initial flow would have to be increased.

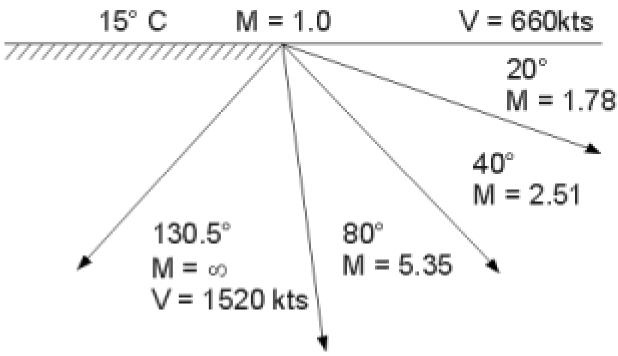


Fig 17 Mach Number Increased Round Expansive Corners

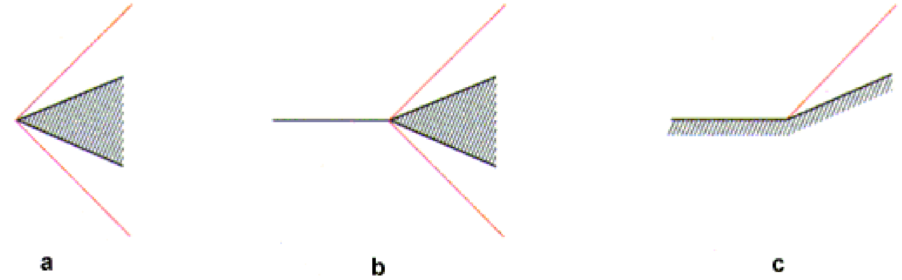
Compressive Corners

48. A compressive corner causes supersonic streamlines to converge, creating a shockwave whose formation can be visualized by treating the corner as a source of pressure waves creating a bow wave. The shockwave exhibits all the characteristics of a bow wave; it first forms as a detached normal shockwave, moves back to the source with an increase in speed, attaches and becomes oblique. Fig 18 illustrates a compressive corner obstructing supersonic flow above M_{DET}.

Nature of a Shockwave

49. **Physical Effects of a Shockwave.** A shockwave is a very narrow region, 1/400 mm thick, within which the air is in a high state of compression. The molecules within the shock are continually being replaced by those from the free flow ahead of the shock. Mach number can be considered as being the ratio of directed energy (DE) to random energy (RE) within the flow. The velocity is a measure of DE whilst RE is related to temperature. On encountering a shockwave, a flow is violently compressed such that some DE is converted to RE (ie velocity is decreased, temperature is increased), the Mach number is reduced, and pressure and density are increased. The total energy of the flow remains constant, but there has been an increase in entropy because of the temperature increase. This process is irreversible. This is significant because this energy is lost to the aircraft and represents drag. It is also the reason why designers try to ensure correct engine intake design for a particular Mach number, the intention being to achieve the deceleration smoothly and with minimum loss of heat energy through as many weak shocks as possible. The stronger the shock, the greater the conversion to heat energy. M =V/a, therefore $M^2 = V^2 / a^2$ which is propotional to kinetic energy/ (T°K) which, in turn, is proportional to directed energy/random energy. Therefore, if DE decreases and RE increases, M^2 decreases.

50. **Normal Shockwave.** A normal shockwave is one perpendicular to the direction of flow. It is always detached from its source, behind it the direction of flow is unchanged and the Mach number is always subsonic (see Fig 19).



A sharp wedge creating an oblique bow shockwave.

A thin plate parallel to the initial flow has been added. This does not influence the flow or shockwave.

The wedge has been divided. A single oblique shockwave is originating from the change in surface direction, the compressive corner.

Fig 18 Supersonic Flow at a Compressive Corner

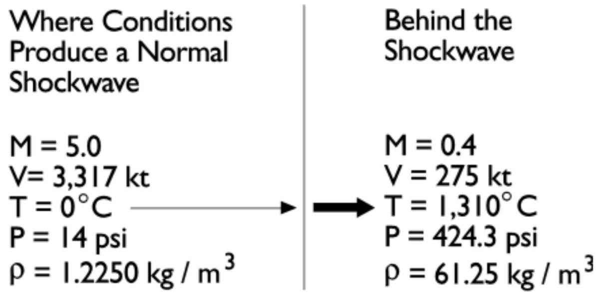


Fig 19 Flow Through a Normal Shockwave

51. **Oblique Shockwave**. The flow behind an oblique shockwave has its Mach number reduced, but if the wave angle (W) is less than about 70° it will still be supersonic. The direction of flow behind an oblique shockwave is turned through an angle equal to the deflection angle of the obstruction giving rise to the shockwave.

52. **Reduction in Flow Speed Behind Oblique Shockwave**. Fig 20 shows why the reduction in flow speed behind an oblique shockwave is less than that behind a normal shockwave. The actual approach flow has been resolved into two vectors thus:

a. X is the component normal to the shockwave and is therefore affected by it.

b. Y is the component parallel to the shockwave and is therefore unaffected by it.

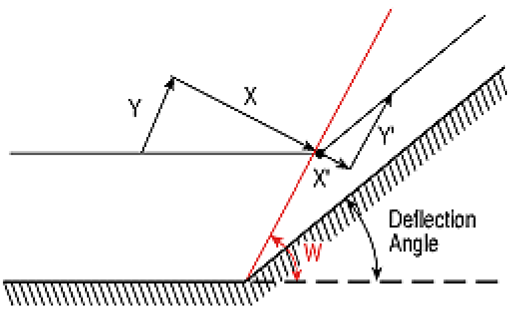


Fig 20 Flow Through an Oblique Shockwave

Once the flow has passed through the shockwave:

c. Component X has been reduced to a subsonic value, X'.

d. Component Y is unaffected.

e. The flow Mach number has been reduced and travels parallel to the new surface.

With the foregoing in mind two very important statements can be made about the pressures experienced round an aircraft above M_{DET}:

f. All forward-facing surfaces experience greater than atmospheric pressure.

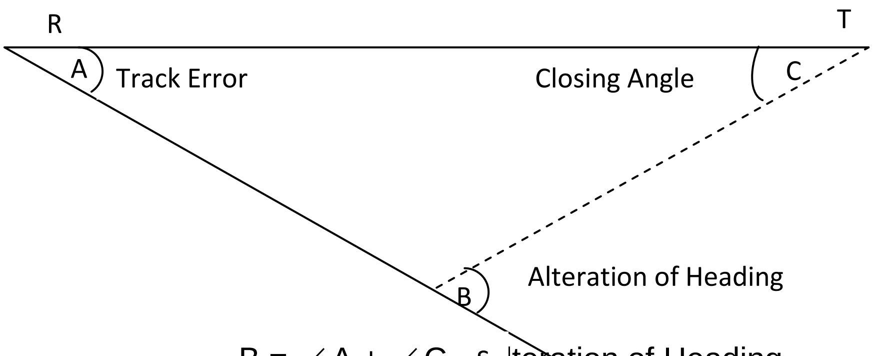
g. All rearward-facing surfaces experience less than atmospheric pressure.

TOPIC – 5 : NAVIGATION

ALTERNATION OF HEADING

1. If you plan correctly and fly accurately then your nav ex will go as excepted and your main task will be that of monitoring. However you will find that forecast winds will not always be correct and that your flying is inaccurate resulting in your drifting off planned track. You must therefore know how to make suitable heading alteration to enable you to reach the required turning point.

2. **Identification of Angles**. First, it is necessary to identify the angles associated with an alteration of heading calculation. In the diagram below RT is the planned track of an aircraft. The aircraft is fixed off track at S.



$B = \angle A + \angle C$ Alteration of Heading

Fig 01

If the aircraft is then flown from S to T, the new track the line is called the TRACK MADE GOOD, the actual track flown. Learn to recognise the following angles. It should be noted that through this chapter angles have been exaggerated for clearly:

a. **Track Error**. Angle A, the angle between planned track and track made good is known as track error.

b. **Alternation of Heading**. Angle B, the amount of turning necessary at the fix to make good the destination at T, is known as the alteration of heading (AH).

c. **Closing Angle**. Angle C, the angle between the new track and the original planned track at the destination, is known as the closing angle. This is the angled used to calculate alteration of heading.

3. **Estimation of Closing Angle**. You have already prepared a map with 5^0 bearing line drawn to the turning point. This line is drawn to assist in the estimation of closing Angle. The following examples illustrate the use of the 5^0 bearing line:

a. An aircraft's planned track is the line AB. It is fixed off track at C. By estimation, the closing angle to B from C is 3^0 to the left of track

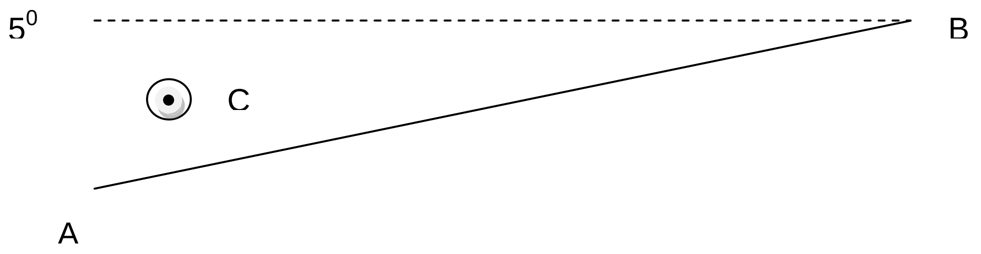


Fig 02

b. An aircraft's planned track is the line DE. It is off track at F.

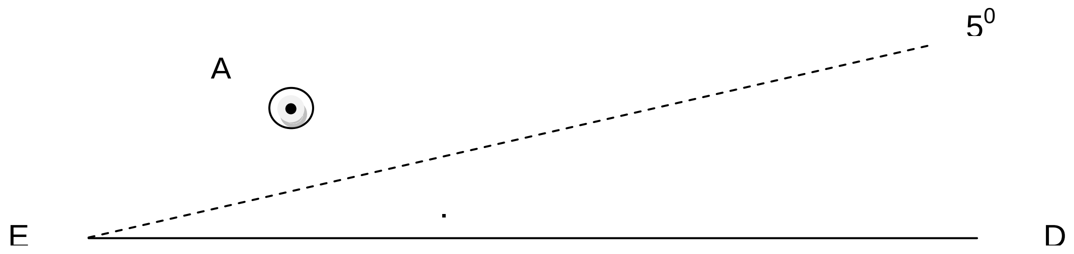


Fig 03

By estimation, the closing angle from F to E is 7^0 left of track. You should note that the closer the fix is to the turning point, the greater is the closing angle for the same distance off track. It will help if you imagine a 10^0 line drawn on the diagram.

c. The bearing line is a sufficient guide when the aircraft is fixed off the opposite side of track. For example an aircraft's planned tracks is line CH and it is fixed off track at J.

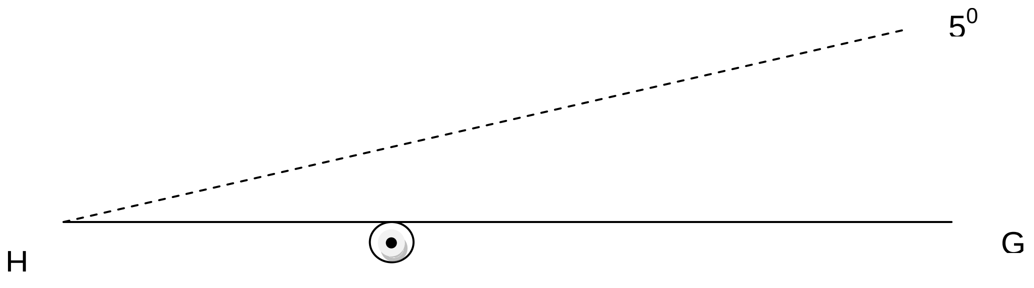


Fig 04

By estimation, the closing angle from J to H is 7^0 from the right.

4. **The one in sixty Rule.** Most pilot alterations of heading are based on the 1-in-60 rule. The explain its derivations, consider a circle of radius 60 units.

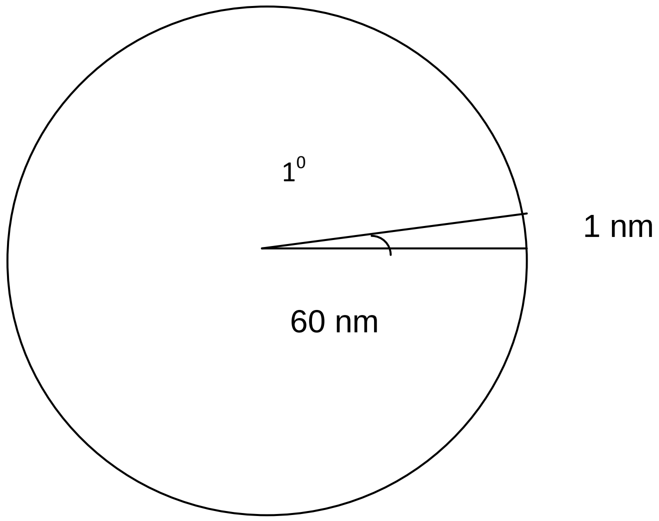


Fig - 5

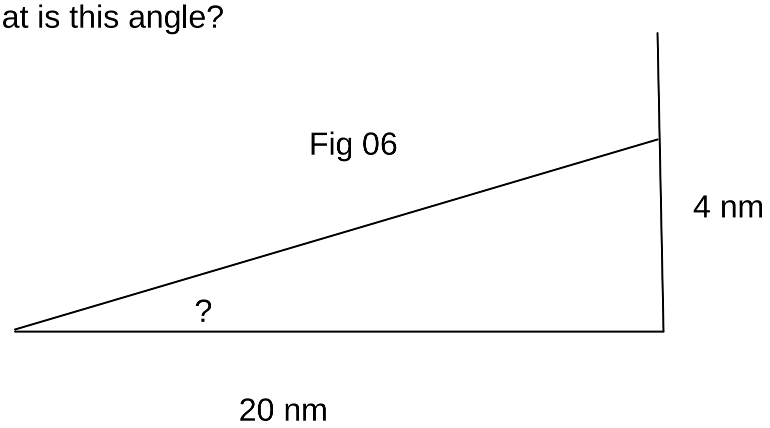
Let 1 unit substend an angle of x^0 in the segment. The circumference of a circle is 2 $\pi\gamma$

If we say π =3 then the circumference of our circle is 2x3x60 one digit will subtend 1/360 of the angle of a circle,

ie $\frac{1\text{x}360^0}{360} = 1^0$

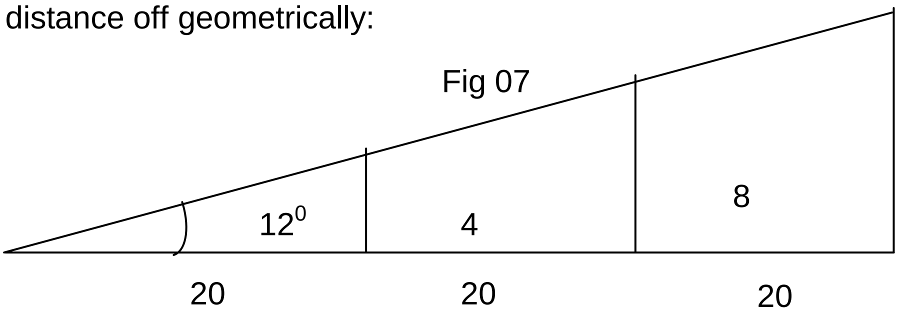
Note that if the exact figure were used, we would finish up with a 1 in 57 rule. So one mile off in 60 subtends 1^0, 2 miles off in 60 subtend 2^0, etc but what happen if the base is not 60? For example what is this angle?

Fig 06



The answer, of course, is 12^0. What you did was to mentally project the base to 60 and enlarge the distance off geometrically:

Fig 07



In other words you worked out how many times the distance along went into 60 and multiplied by the distance off:

$$\text{Angle} = \frac{\text{Distance off Track}}{\text{Distance Go/To Go}} \text{X } 60$$

This formula is most useful when the figures are complicated. To put all this in perspective, here is a typical pilot navigation problem:

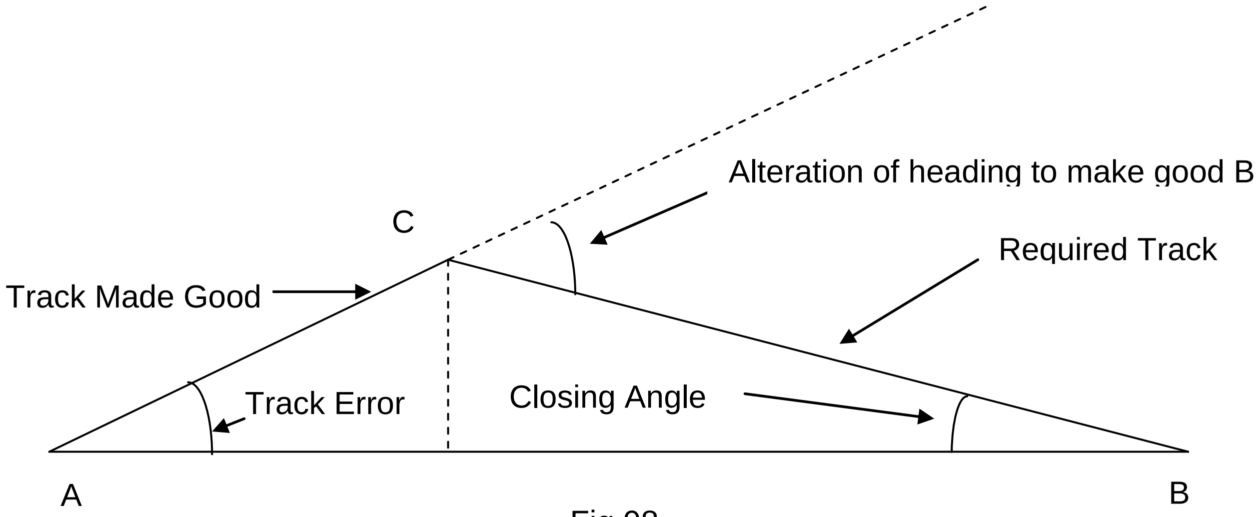


Fig 08

In medium level navigation, alterations of heading are calculated to make good turning points. In the diagram, the alternation of heading is equal to the sum of the Track Error and Closing Angle (exterior angle = sum of the 2 interior opposite angles).

Therefore, A/H = $\frac{CD}{AD\,(\text{ or }AC)} \text{ X } 60 + \frac{CD}{DB\,(\text{ or }CB\,)} \text{ X } 60$

Bearing in mind that the 1-in-60 rule is derived from a circle, the accuracy of the formula is as follows:

a. Tan function may be used up to 25^0

b. Sine function is accurate up to 40^0

c. Up to 70^0, the sine function is accurate to within 10%

5. **<u>Proportion of New Track Flown</u>**. Secondly it is necessary to make an estimate of the proportion of new track flown at the time of the fix so that alteration of heading may be calculated. This is a very simple estimate and is made in terms for thirds or quarters.

06. **<u>Estimate of Proportion</u>**. The following examples illustrate the estimation of proportion:

a. An aircraft's planned track is the line AB. The last accurate fix was A and it is now fixed at C.

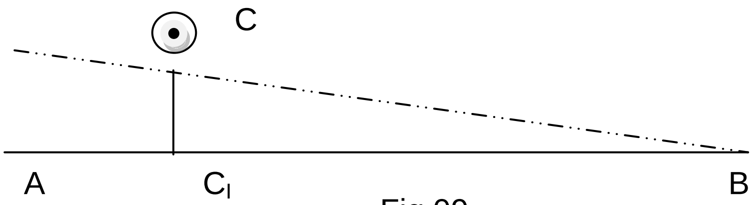


Fig 09

Although the track made good is ACB, for the purpose of estimation the position of C is projected on to AB at C^1. The proportion of new track flown is assessed in terms of AC^1. This is an acceptable approximation because the closing angle is normally a small angle.

Thus the proportion of new track flown = $\frac{AC^1}{AB} = \frac{2}{3}$

a. An aircraft's planned track is the line DE. It is accurately fixed off track at F and a further fix is made at C.

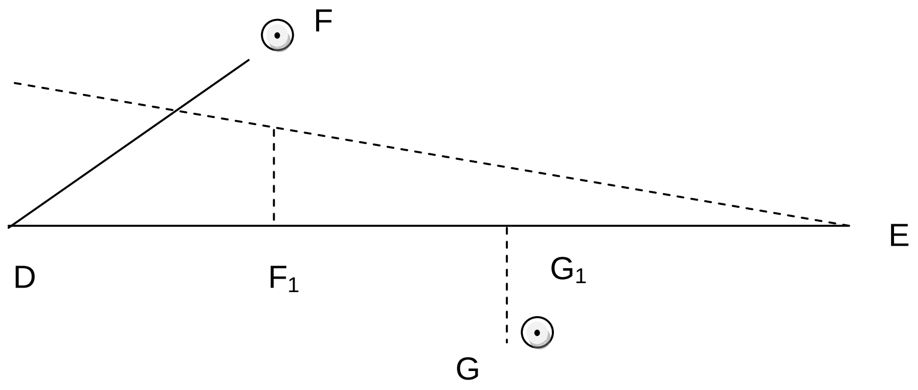


Fig 10

At G proportion of track flown since the last fix is estimated from F as $\frac{F_1\,G_1}{F\,E} = \frac{1}{4}$

EXERCISE 2

An aircraft's planned track is HJ. At k it is accurately fixed off track and a further fix is made at L. Study the diagram below and estimate the proportion of track flown since the last fix.

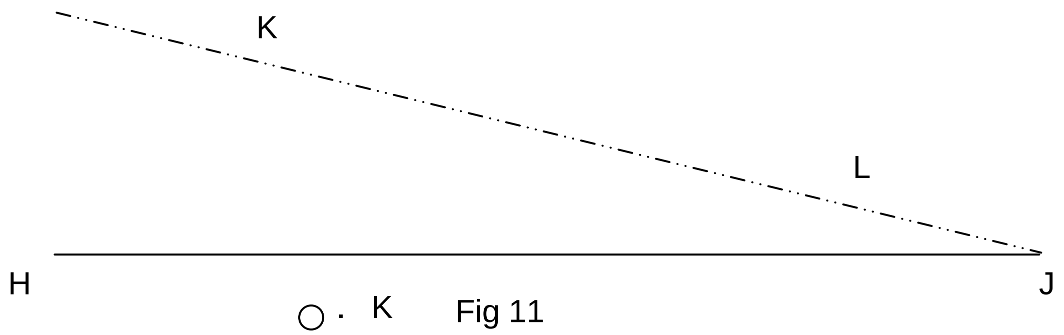


Fig 11

7. **<u>New Track Reference Technique (NTR) or Closing Angle Method</u>.** The 1-in-60 rule is easy to use if only one alteration of heading per leg is required and you can measure distances with ease, and also good at mental arithmetic. However, it becomes progressively more complicated to estimate the track error and closing angle as second and subsequent alterations to heading are made. The new Track Reference (NTR) Technique is solely concerned with the closing angle (readily estimated by a predawn 5^0 bearing line) and simple proportions off track flown. The following is one method of proving the formula:

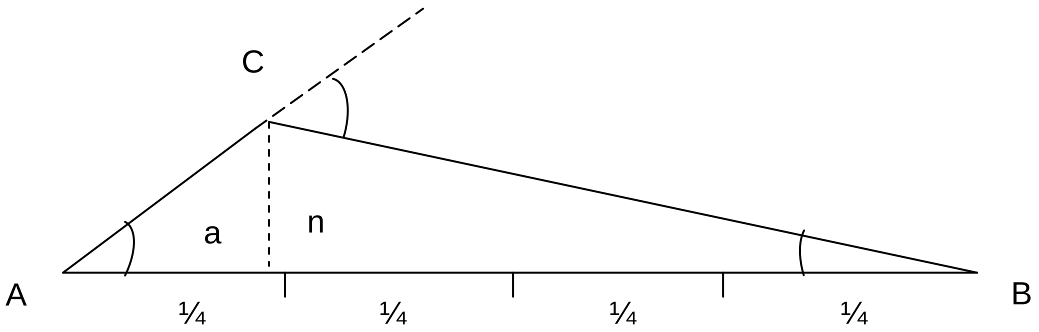


Fig 12

Consider an aircraft n miles off track at C, of the way along track and needing an A/H to make good B. Using the 1 in 60 rules:

Angle a = x 60 and angle b = x 60

or = n x 60 and b = n = 60

Equating n x 60, we have a = b

Multiply each side by 4, a = 3b

But A/H = Track Error + Closing Angle = a + b = 3b + b = 4b

Note that having travelled of the way along track the alteration of heading is 4 times the closing angle. The formula can be expressed thus:

$$\text{A/H = closing Angle} \quad \frac{x\,1}{\text{Proportion of Track Flown}}$$

This may sound complicated but, in fact, is not. A few example will help you sort it out.

<u>Example 1</u>

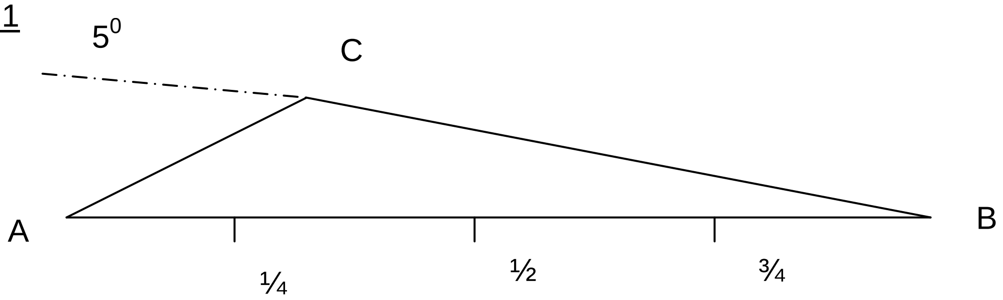


Fig 13

you find yourself over C enroute A to B. Your closing angle is 5 and you are of the way along track. Your alternation of heading is 5 x = 20^0 and the alteration is obviously to starboard.

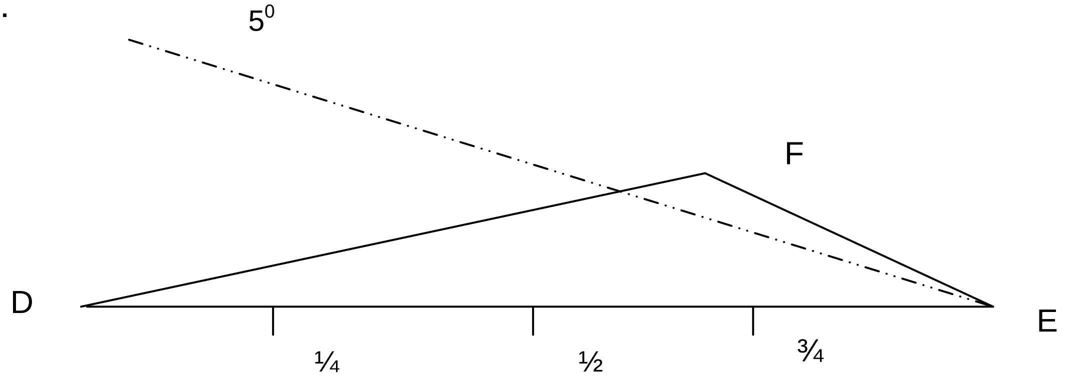


Fig 14

You pinpoint yourself at F enroute D-E. You are ¾ of the way along track and the closing angle is 9^0 (estimate from the 5^0 bearing line). Your alteration of heading is 9 x = 12^0 and again the alteration is to starboard.

8. **Second Alteration of Heading**. Let us look at the case where a pilot has made an alteration of heading and then fixed himself again and a second alteration of heading is required.

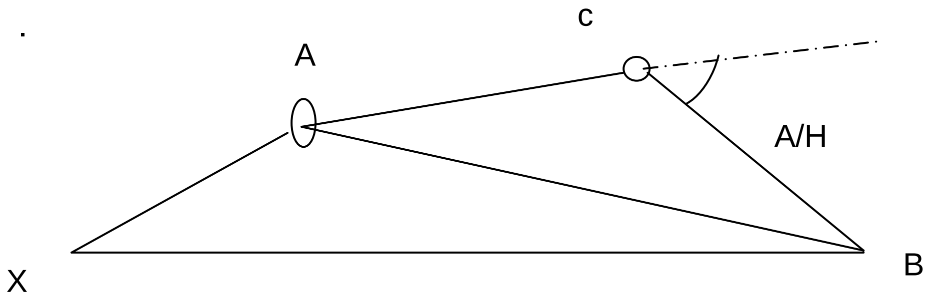


Fig 15

The planned track is XB, the first fix was at A and the subsequent fix was at C. The triangle ABC has been purposely drawn to resemble the triangle ABC in para 8 to emphasise the point that the calculation is now related to $\angle$ABC, the change in closing angle, and not to $\angle$XBC, based on the original planned track in addition the proportion of track flown is the proportion of NEW track flown since the last fix at A. Thus for a second or further fix track alteration of heading equals the (change of closing angle since last fix) x (reciprocal of proportion of track flown since last fix).

i.e. Alteration of Heading = Change of C/A × $\frac{\text{Dist between last fix and turning point}}{\text{Dist between last fix to present fix}}$

9. No Heading Change, If, when the fix at C was taken, it was found that the aircraft was along the line AB then, although it was fixed of the original planned track, there would be no change of closing angle and consequently no alteration of heading necessary. The fix confirmed the aircraft was on its new track.

10. **Fixes on Opposite sides of Track.**

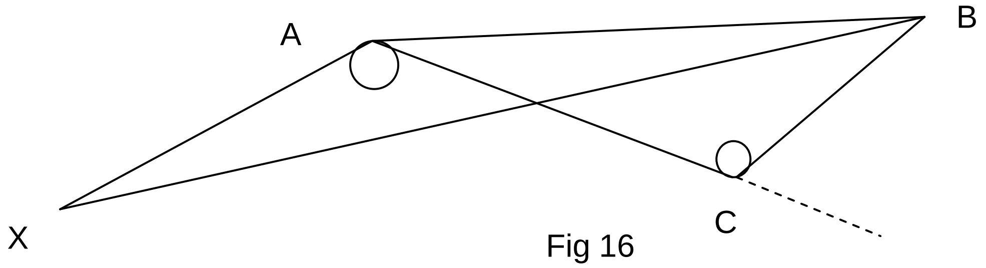


Fig 16

of successive closing angles are of opposite sides of the planned track then the algebraic difference, $\angle$ABC is the sum of the 2 successive closing angles.

11. **Examples**. The following illustrate the calculation of alteration of heading in various situations:

a. An aircrafts planned track is the line MN. The pilot fixes himself at R, and then later at Q. What alterations of heading are necessary?

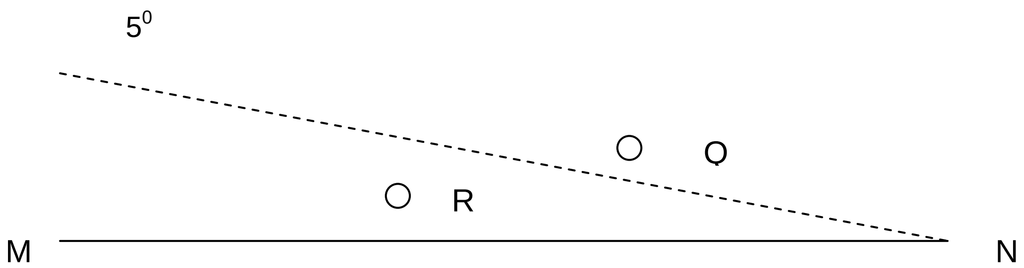


Fig 17

At R, the closing angle is about 4^0 and the proportion along track $\frac{1}{3}$. Thus A/H = 4 x 3 = 12^0 (S). Remember you must always specify the direction of A/H port or starboard. At Q, the closing angle is about 6^0 (giving a change of closing angle 2^0) and the proportion along new track is 2.

Thus A/H = 2 x 2 = 4^0 (S).

b. An aircraft's planned track is the line AB, the first fix is a C and the second at D. What alteration of heading are needed?

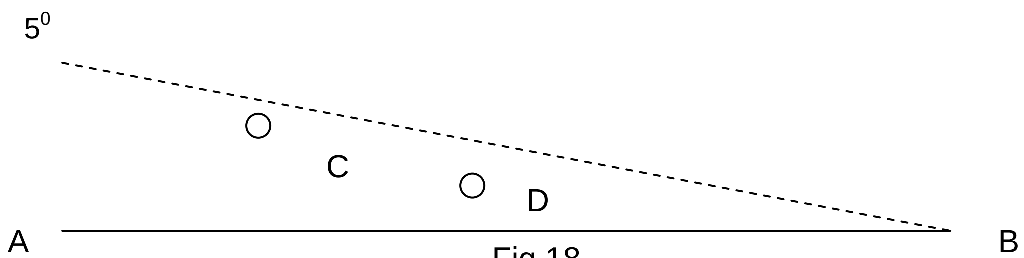


Fig 18

At C, closing angle is about 3^0 and the proportion along track $\frac{1}{4}$

A/H = 3x $\frac{4}{1} = 12^0$ (S)

at D, the closing angle is about 2^0 (giving a change of closing angle of 1) and the proportion along ne track is $\frac{1}{3}$ Thus A/H = 1 x $\frac{3}{1} = 3^0$ (P)

Note that in this case the alteration in heading is away from planned track.

c. An aircraft's planned track is the line FC. The pilot fixes himself at X, then at Y and then again at Z. What alterations of heading are necessary?

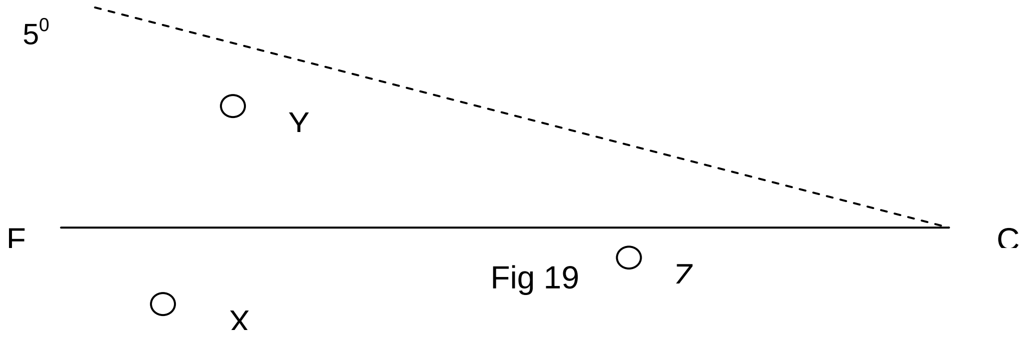


Fig 19

At X, closing angle is about 5^0 and proportion along track is ¼ . This A/H = 5 x ¼ = 20^0 (P). At Y, change in closing angle is 5+3=8^0 and proportion along track is 1/3. Thus A/H = 8 x 3/1 = 24^0 (8) at Z, change in closing angle is 3+10=13^0 and proportion along track is

Thus A/H = 13 x 3/2 = 20^0 (P) (When rounded up to nearest degree).

12. In each of the following 3 questions AB is a planned track and fixes are made at the points shown. In each case calculate the necessary alteration of heading part or starboard to reach the turning point B.

a.

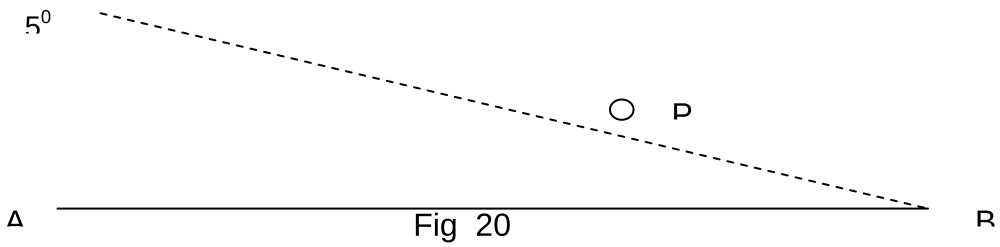


Fig 20

b.

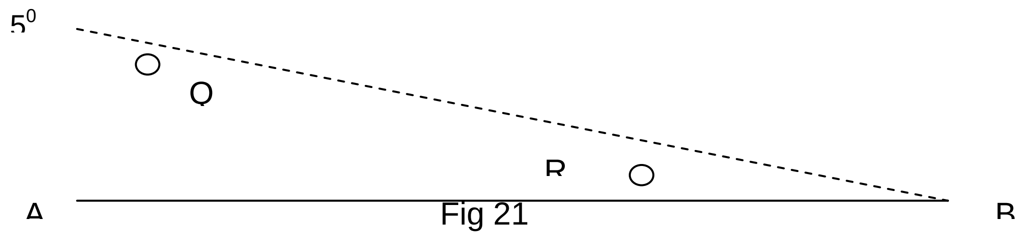


Fig 21

c.

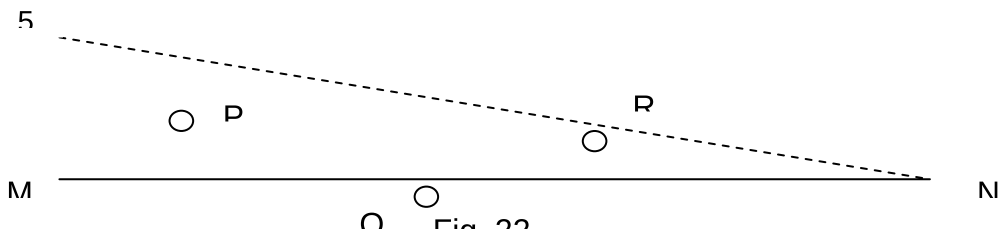


Fig 22

13. **<u>Alteration of heading when turning on ETA</u>.** An occasion should be noted When the new track reference technique is not used for alteration of heading. This occasion is when making an alteration of heading after turning on times at a turning point when not in visual contact with the ground. You will see from the diagram that if you have turned early of late your heading may be correct and you are flying parallel to your planned track. In this situation your alteration of heading following your first fix needs to be by CLOSING ANGLE ONLY.

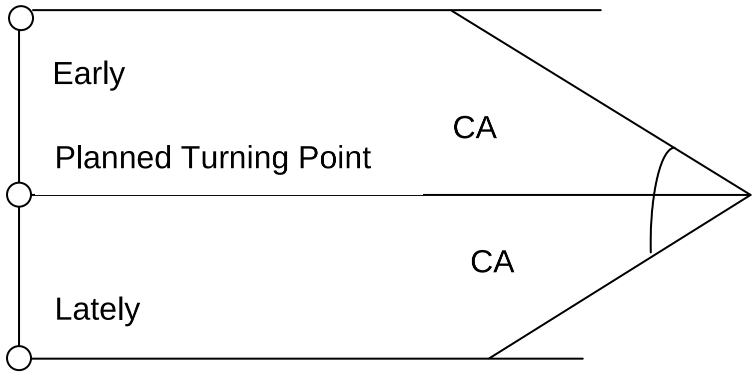


Fig 23

You will realize that the alteration of heading based on the new track reference technique was based on the sum of the closing angle and the track error. In this case track error is zero because you are flying parallel to planned track and therefore the alteration of heading is equal to the closing angle only. For all subsequent fixes along the leg, the new track reference method of altering heading is to be followed.

<u>STANDARD CLOSING ANGLE</u>

14. The standard closing angle (SCA) method of regaining track is used when a position is fixed off track but no feature on track is visible and no suitable funnel feature is available to assist regaining track. The SCA is based on the 1 in 60 rule and is a closing angle determined by the speed of the aircraft. An alteration of heading equal to this standard closing angle is made and held for a time dependent upon the distance off track. At the end of this time the original heading is resumed along the required track.

15. **Explanation of Formula**

$$\text{Standard Closing Angle} = \frac{60}{\text{ground speed in nm / min}}$$

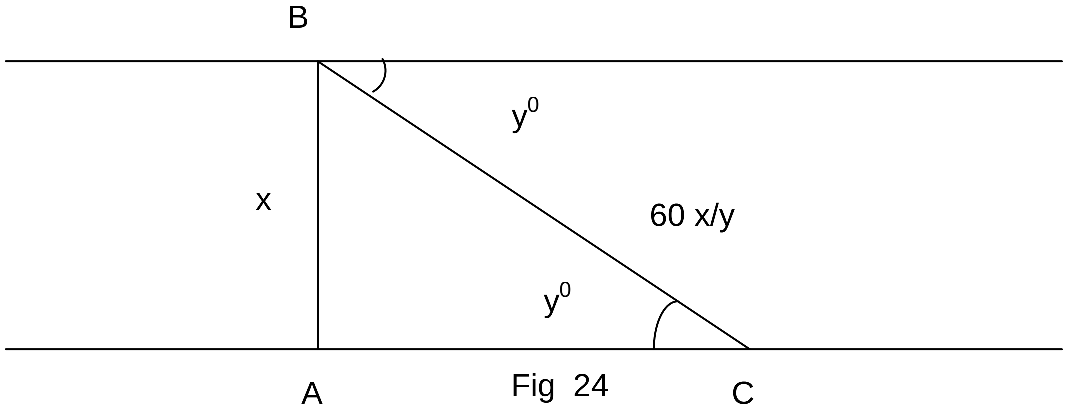


Fig 24

Consider an aircraft at B x nm off from the planned track and flying parallel to this track. We wish to calculate the SCA, the angle Y^0, with which the aircraft must close with track. Let us assume the aircraft has a groundspeed of z nm/min. From the 1 in 60 rule the distance to fly to regain track is $60^x/y$ nm. Now the method is based on holding the alteration of heading (Y^0) for a time is minutes (x minutes) equal to the displacement for track in nautical miles (x nm). To fly a distance of $60^x/y$ nm in x min the ground speed of the aircraft must be:

$$\frac{\text{DISTANCE}}{\text{TIME}} = \frac{60x}{xy} = \frac{60}{y} \text{ nm / min}$$

But the ground speed of the aircraft is z nm/nim. Therefore 60/y

$$\text{Thus SCA} = \frac{60}{\text{ground speed in nm/min}}$$

Assuming that the aircraft is flying parallel to planned track, the alteration of heading is equal to the SCA held for a time in minutes equal to the displacement from track in nautical miles.

16. **Example.** For an aircraft flying at 3 $\frac{1}{2}$ nm/min and fixed 2 miles off track SCA

60/ = 17^0 and this alteration of heading would be held for 2 min to regain track. If the aircraft is fixed right of track than the alteration of heading would be 17^0 P.

EXERCISE-1

Calculate the SCA for:

a. A FOUGA Flying at 210 kts SCA = $\frac{60}{\text{grd sp din nm/min}} = 17^0$

b. A JIP 5A flying at 240 kts SCA =

TIMING

Introduction

1. Many air operations require that aircraft reach a given point at a precise time. As it is usually easier to lose time than to gain it, such operations are often planned with a margin of time in hand. Whether or not this is done, some adjustment to the speed or to the distance to be flown will invariably be necessary to achieve the planned arrival time.

TIMING BY SPEED ADJUSTMENT

General

2. The obvious way to alter an aircraft's time of arrival at its target is to increase or decrease the airspeed thus changing the groundspeed. If the aircraft is equipped with a doppler or inertial navigation system it is more convenient to base adjustments directly on groundspeed.

3. Only a small increase above the standard operating speed of an aircraft at a given height is normally possible without an appreciable penalty in fuel consumption. Small speed changes result is only small increases or decreases in flight time. For example, at a groundspeed of 200 knots an adjustment in groundspeed of 10 knots will gain or loss three minutes in an hour; the same adjustment at 400 knots gives a difference of only one and a half minutes per hour. If therefore accurate timing at the target is to be achieved by speed adjustments, action must be initiated as early as possible. The ideal is to be on time at the beginning of a flight and stay on time by adjusting the speed at each fix.

4. Two factors usually tell against attainment of the ideal. If operating in an area not served by a reliable wind forecasting service, a situation more common operationally than in training, to stay on time during the early part of the flight might lead to impracticable speed changes being required when near the target, to compensate for major changes from forecast head or tail wind component. Further, more frequent speed changes when operating high performance aircraft are expensive in fuel. It is therefore good practice to make only one or two adjustments to speed in the early stages of the flight, and changes at turning points are usually adequate. The aim is to stay nearly on time but with a progressively decreasing amount of time in hand, arriving on time at a suitable way point near enough to the target to allow any reasonable wind changes to be taken care of by speed adjustment. From that way point to the target timing is checked and speed adjusted at each fix.

Calculation of speed Adjustment.

5. The required groundspeed changes can be calculated as follows:

a. On the Dead Reckoning computer, by calculating the groundspeed required between a fix and the next turning point from time and distance to go.

b. By the use of tables, prepared for the usual operating speeds, giving the amount of time gained or lost if various speed changes are applied for a given period.

c. By using annotations made on the flight plan of the airspeed adjustments required to gain or loss one minute, computer for each leg.

d. By estimation in flight using MDR techniques.

6. Of these methods, that in sub-para 5a is the one most commonly used by navigators.

Change of Mach Number

07. When an aircraft is being flown by reference to a mach meter rather than an airspeed indicator, an adjustment to indicated Mach Number to gain or loss time can be calculated as follows:

a. **Computer Method**:

(1) Determine the present groundspeed.

(2) Determine the groundspeed required to make good the required ETA.

(3) Calculate on the computer a new mach number to fly, using the following formals:

$$\frac{\text{Current Mach No}}{\text{Current G/S}} = \frac{\text{New Mach No}}{\text{Required G/S}}$$

b. **Use of Timing Graph.** The change in Mach number required can be determined directly from a graph (Such as that illustrated at Fig 1) as follows:

(1) Calculate the ETA using the current groundspeed and the distance to go.

(2) From this ETA and the required ETA determine the amount early or late.

(3) Enter the graph with distance to and correct groundspeed, extract the Mach Number change required to gain or loss one minute, and by proportion determine the mach change needed.

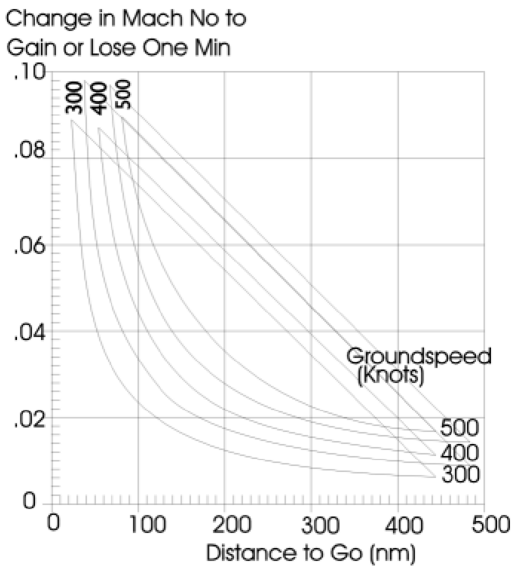


Fig 1 Change of Mach Number to Gain or Lose Time

TIMING BY ADJUSTMENT OF DISTANCE TO BE FLOWN

General

8. It may sometimes be desirable to adjust timing by altering the distance to go rather than changing airspeed. The various methods of doing this, some of them requiring preplanning and some not, are described in the following paragraphs.

Losing Time by 60^0 Dog-leg

9. Heading is altered 60° in either direction for the length of time that is to be lost, then altered 120° in the opposite direction for the same length of time to regain track. Heading to the next turning point or target is then resumed. The aircraft will thus have flown two sides of an equilateral triangle, and the time lost will be equal to the time taken to fly one side.

10. Small inaccuracies in tracking and time lost will be introduced by the wind effect during the procedure, but they will usually by negligible if the amount of time to be lost is small. If the same constant rate of turn is maintained throughout the three turns, and if legs are timed accurately from levelling out after a turn to the start of the next turn (see Fig 2), the effect on time lost of the time taken to turn can be ignored.

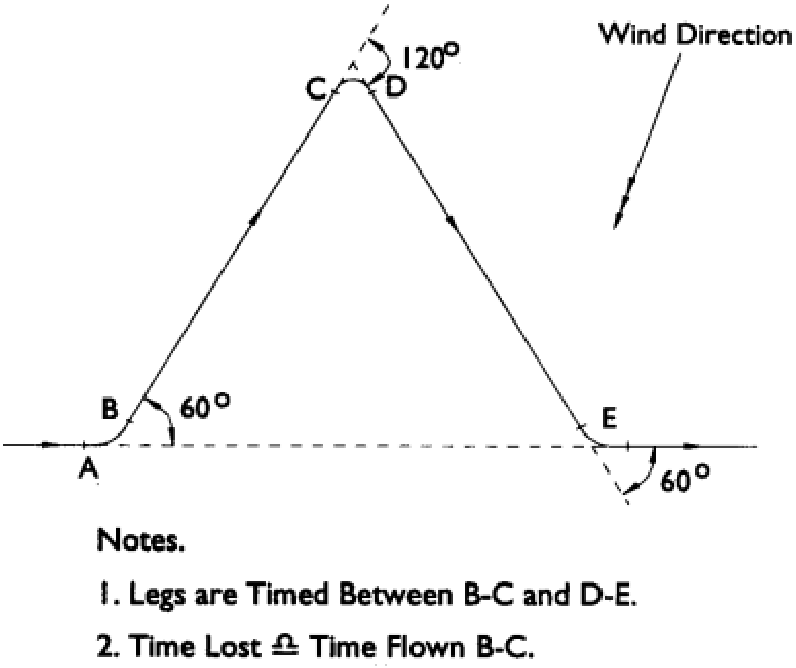


Fig 2 60 degree Dog-leg Procedure

11. The 60^0 dog leg procedure as described above can normally be used for small time loses, but if more than two minutes is to be lost or if the wind is strong, it will be necessary to adjust the time on the second leg to endure that the final turn will bring the aircraft back on track. If this is not done, the resulting track error will leave a further timing problem, particularly if near the next turning point. Where such an adjustment will be necessary, it is usual to make the first turn towards the “into wind” direction. This will ensure that track can be rejoined with time in hand, and that it will not be necessary to extend the second leg to regain track, thus putting the aircraft in the more difficult position of having to make up time.

Losing Time by 30^0 Dog-Leg.

12. A similar procedure, altering heading first 30^0 in one direction then 60^0 is the other before resuming heading, may be used for small adjustments in ETA (See Fig 3).

13. For each minute to be lost each leg is flown for four minutes. This procedure is useful for small time losses (up to two mins) when it is desired to stay near track and avoid big alterations of heading.

14. Even when timing is not a consideration, adoption of a formal dog-leg procedure to avoid obstacles or weather will enable the track to be regained and ETA amended with minimum calculation.

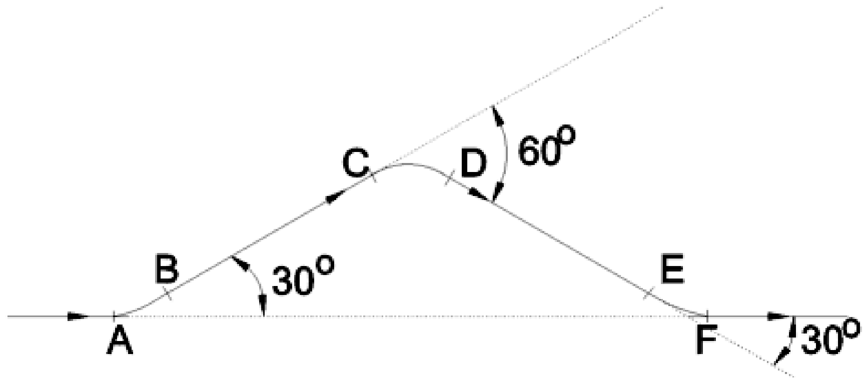


Fig 3 30 degree Dog-leg Procedure

Notes: 1. Legs are timed BC and DC
2. Time lost is 1 min in 8 mins

<u>Losing Time by Rate (90^0 Method)</u>

15. The procedure illustrated at Fig 4 could occasionally be useful in high performance aircraft, but is more likely to be of value to the pilot navigator than to a navigator. The time lost by using the procedure is arrived at as follows:

Distance A-B-C-D = πd (Where "d" is the diameter of turn)

Direct A-B-C-D=2 mins (360^0 at Rate 1)

Direct Distance A-D = 2d

Time A-D = 2d x 2 / πd mins = 4 / π mins = 1′ 15″ (approx)

Time lost = 2′ - 1′ 15″ = 45″ (approx)

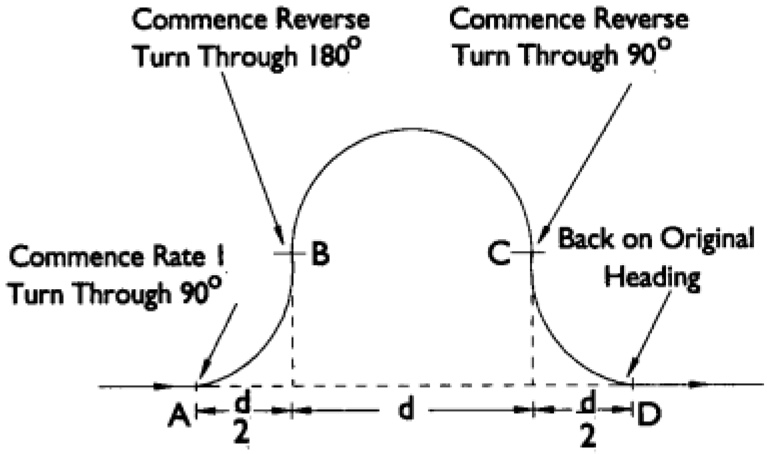


Fig 4 Losing Time by 90 degree Method

16. To lose more than min, substract min from the time to be lost and straighten up between each reverse for half the resultant time.

Summary of Dog-leg and 90^0 Methods.

17. The above methods suffer from the disadvantages that:

a. They are imprecise in track regaining.

b. They are inaccurate in time losing.

18. It is usually necessary for them to be followed by heading correcting, and if precision is required by speed adjustments. They do however serve to lose a lot of time in a short distance along track, but at the expense of considerable deviation from the planned track not always tactically acceptable.

Cutting the Corner.

19. If there is a suitably large track alteration along the route, timing may be adjusted by extending or cutting the corner at that turning point. A simple example of this procedure is shown if Fig 5.

20. Given a route A-B-C (Fig 5a), timing is adjusted by adopting a new turning point in place of position B. As shown in 5a, distances representing 1,2 and 3 minutes of groundspeed are marked along the track BC and its reciprocal, and marked G1,G2 and G3 (gaining time) and L_1L_2 and L_1 (Losing time). If at position X the aircraft were two minutes ahead of time, heading would be altered to fly the track X-L_2C. Where turning circles have to be allowed for, it is convenient to mark the timing points along a line parallel to the track from B to C, passing through the originally planned start turn point at B, as shown in Fig 5b ETA start turn is then easily calculated.

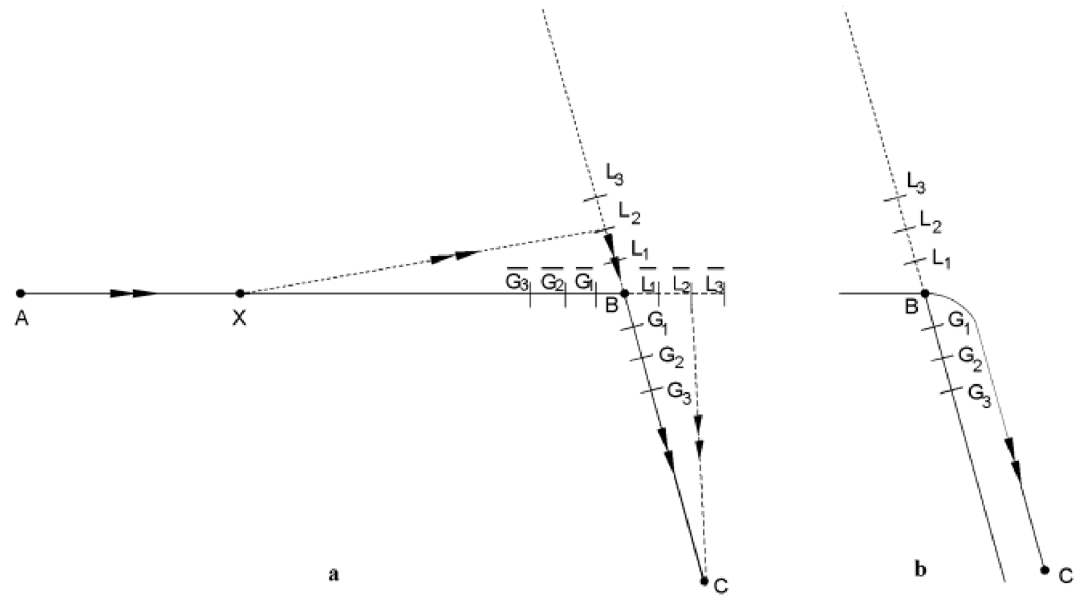


Fig 5 Timing by Adjustment of Track at a Turning Point

21. This system can be used provided that the distance X-B is sufficiently long and the angle of B is such that triangles XBL_3 and XBB_3 may be considered isosceles, so that, for example, XB is approximately equal to XL_2.

Pre-Computed Timing Leg

22. A more precise method of adjusting timing by revising the distance to be flown is to use pre-computed timing legs at any convenient turning point. Use is again made of the principle is isosceles triangles.

23. Fig 6 Shows pre-computed timing legs constructed for the route A-B-C. At position B a line BDE is drawn at an angle of 75^0 to track BC. The length of BD is the distance flown in, say, four minutes where three minutes is the longest period it is thought it will be necessary to make up at that turning point. Similarly DE is the distance flown in the maximum time it will be necessary to lose. From D line BDE is divided into units of distance flown in one minute, and marked G1, G2, L1, L2 etc as shown.

24. A line DF is drawn at an angle of 75^0 to BD to intercept BC at F, A-B-D-F is now the “On time” track, used in calculating the required set heading time when completing the flight plan. The dotted line in Fig 6 illustrates the track to gain two minutes. A method of construction when allowance must be made for turning circle is shown in the inset to Fig 6.

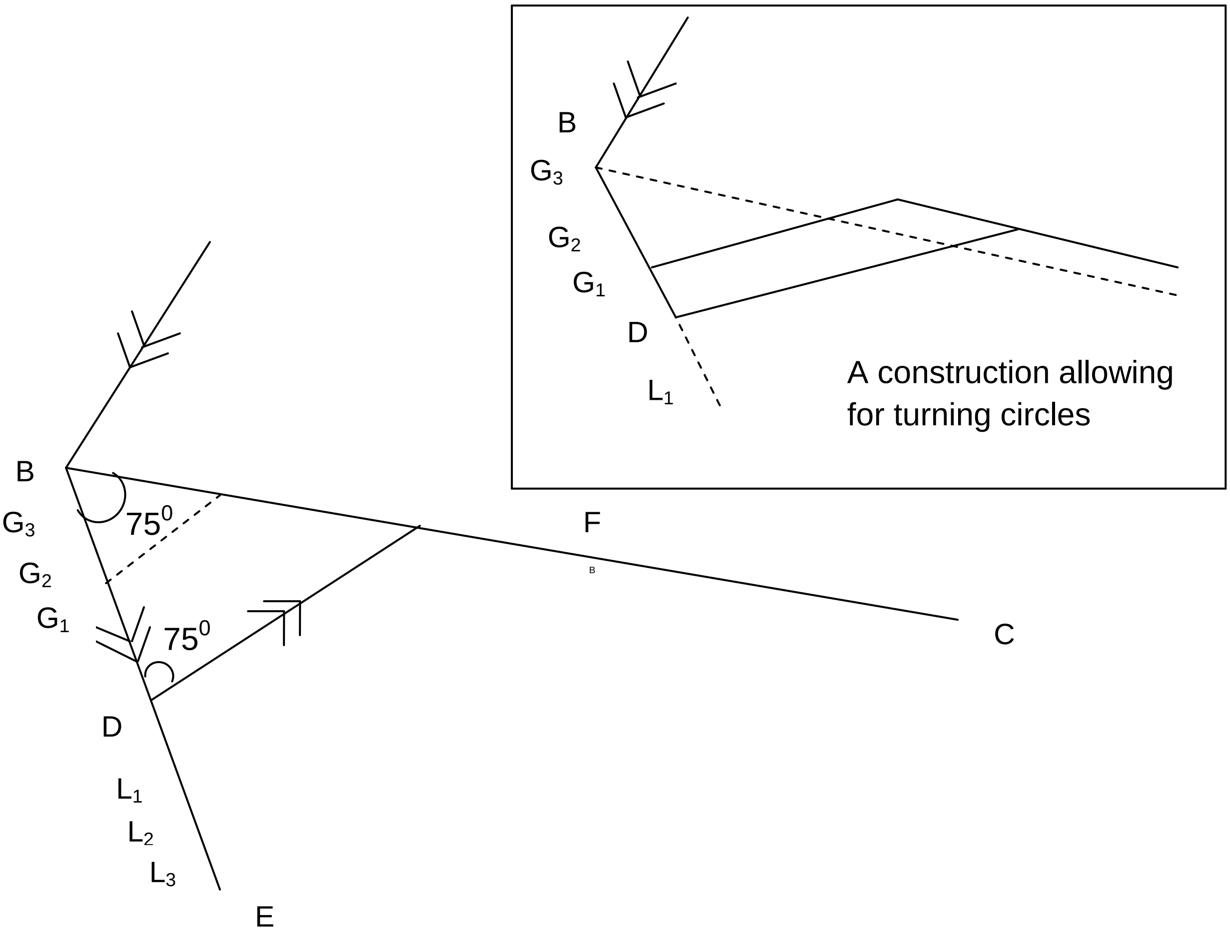


Fig 6 Pre-computed Timing Legs

25. **<u>Use of Tables and Graphs</u>.** When an aircraft type is being flown regularly in the same flight profile, it may be useful to carry a table or graph showing the gain or loss of time resulting from the application of changes in IAS (at say 20 k intervals of IAS) for a convenient period of time.

26. **<u>Estimating Adjustments to Flight Plan IAS in Flight</u>.** This is best explained by an illustration. Suppose that a leg is being flown at an IAS of 360 k, and the ground speed gives a flight plan time of 80 mins. At a pin-point estimated to be one quarter along the leg the aircraft is one minute late. If no adjustment is made the aircraft will be 4 mins late at the turning point. To be on time at the turning point the remainder of the leg must be flown in 59 mins. These figures of time late and timed to go are applied as follows:

Increase in IAS required

$$= \frac{\text{IAS X Time late on etaTime}}{\text{Time required to ETA}}$$

$$= \frac{360 \text{ X } 4}{59}$$

$$= \frac{360 \text{ X } 4 \text{ (approx)}}{60}$$

= 24 knots

27. **Application of the Rule of Five**. Probably the simplest way to estimate a speed adjustment to gain or lose time is to employ the rule of five, an adaptation of the one in sixty rule.

Adjust speed by an amount equal to 5 times to ground speed in nautical miles per minute, and hold the new speed for a number of minutes equal to one fifth of the number of seconds early or late. Examples are:

a. Speed 360 k, 30 secs late. Increase speed by 30 k for 6 mins.

b. Speed 420 k, 20 secs early. Reduce speed by 35 k for 4 mins.

28. Points to note about the rule of five are:

a. Flying at an airspeed to give a ground speed which is a whole multiple of 60 k simplifies the procedure.

b. To avoid minor speed changes it is sometimes easier to double the speed change and have the time.

c. If it is desired to avoid frequent speed changes, after timing has been regained the aircraft should not revert to the original IAS, but to a speed which will maintain the original ETA, is restore the flight plan ground speed.

d. This system can be applied as soon as a timing error is detected, thus reducing the risk of regaining time by airspeed adjustment needing a change to a speed outside the practical operating limits of the aircraft.

GENERAL CONSIDERATIONS

Accuracy

29. Accurate flying and navigation are essential to successful timing. Turns should be executed at the planned rate of turn, and the aircraft flown at the correct airspeed and altitude. Track keeping is important attempts to make up or lose time by speed adjustment will be negated if the aircraft is allowed to stay far from the planned track.

Early Remedial Action

30. The task of arriving at a target or destination on time will be simplified if any tendency to gain or lose time is quickly recognized, and if remedial action is taken before, too big an error, has accumulated. When the aircraft is early, care must be taken to ensure, before shedding all the time in hand, that the planned route for the remainder of the flight to the target, coupled with practicable speed adjustments, gives sufficient flexibility to make up any foreseeable subsequent loss of time.