CHAPTER 2

ELEMENTARY PRINCIPLES OF FLIGHT

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Introduction

1. The earth is surrounded by a compressible fluid commonly referred to as the atmosphere or air. All bodies which in flight rely upon fixed or moving wings for their support can only remain in flight while surrounded by air.

2. Since the air is a fluid its state will change easily with a change of temperature or pressure, both these factors having a marked effect on its density. Since high density will readily support a body in flight but will retard forward movement, it follows that high speed flight can be more easily achieved at the higher altitudes where the density is lower.

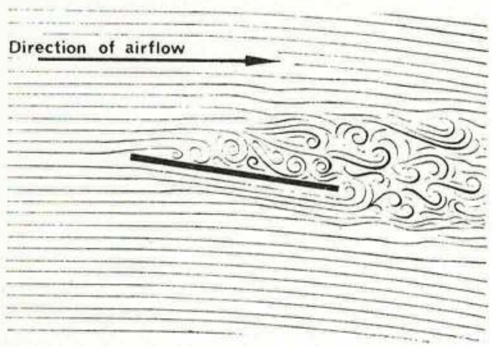


Fig. 1. Airflow over a flat plate.

Aerofoils and Airflow

3. When air is caused to flow past a flat plate inclined at a small angle to the airflow (Fig. 1) the pressure of the air above the plate is decreased and the pressure below the plate is increased. These changes are brought about by the disruption of the smooth airflow and the resultant force is known as total reaction. Total reaction has two components one known as lift which is measured upwards at right angles to the direction of airflow and the other known as drag which is measured rearwards in line with the airflow.

Lift and Drag

4. When an aircraft is in steady horizontal flight, lift is the upward vertical force opposing the downward vertical force which is the weight of the aircraft. The force which causes the aircraft to move forward is known as thrust and the force which resists the forward motion is known as drag. Lift is the useful component of total reaction and drag is the undesirable component. To obtain maximum lift the reaction line should be as near perpendicular as possible. The flat platc in Fig. 2 shows a poor reaction angle. Lift is also dependent upon smooth airflow and air flowing over the top surface of a flat plate becomes turbulent at very small angles. A flat plate is a poor shape for an aircraft wing.

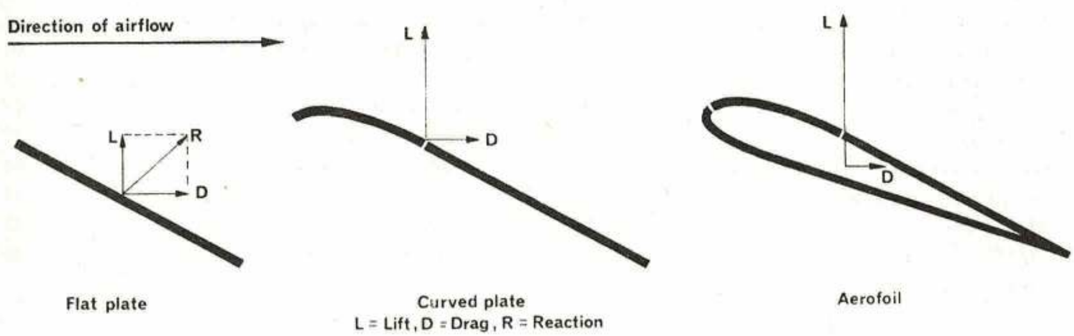


Fig. 2. Evolution of aerofoil.

Aerofoil Shape

5. It was found that by adding curvature to the leading edge of the flat plate the air flowed over the top surface at a greater velocity thus creating a further decrease of pressure; also the airflow remained smooth at a greater angle and the reaction line was nearer perpendicular. The shape was still not ideal as the flat plate could not accommodate strengthening members and so the shape was changed to produce the aerofoil (Fig. 2). An aerofoil may be defined as a structure designed to obtain reaction from the atmosphere at right angles to its direction of motion.

Aerofoil Lift

6. A wing of aerofoil section may under certain circumstances obtain as much as 70% of its lift from the upper surface and only 30% from the lower surface. The lift from the lower surface results from the increased pressure exerted by the airflow while the high percentage of lift gained from the upper surface results from the venturi effect that is to say the increased velocity of the airflow over the upper surface results in a decrease of pressure on the upper surface.

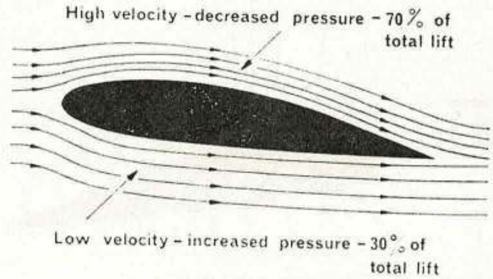


Fig. 3. Aerofoil lift.

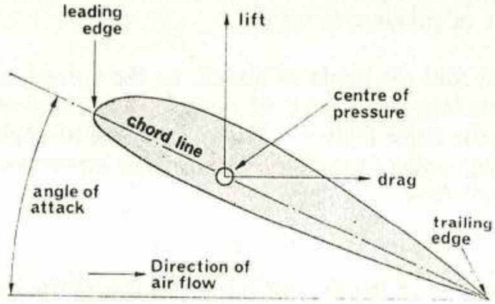


Fig. 4. Aerofoil terms.

7. The upper surface pressure drop and the under surface pressure rise are both at their greatest near the leading edge and at their smallest near the trailing edge of an aerofoil; the pressure distribution will therefore not be constant over the surfaces. The lines representing the airflow in Fig. 3 are termed streamlines and when they are shown close together high velocity is indicated, and low velocity shown when they are widely separated.

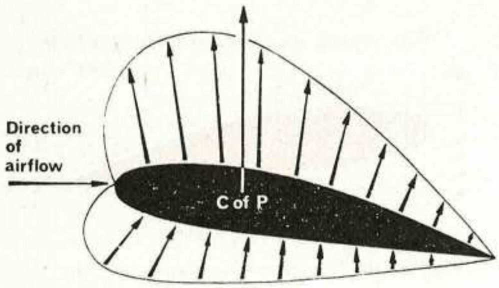
Angle of Attack

8. The amount of lift derived from an aerofoil for a given airspeed is dependent upon the angle of attack, that is to say the angle the chord line (Fig. 4) makes to the direction of airflow. The chord line is an imaginary straight line joining the leading edge to the trailing edge. Maximum lift is reached at an angle of about 15° but the drag component also increases progressively, so each aerofoil has an optimum angle of attack namely the greatest number of pounds lift per pound of drag, known as the lift/drag ratio.

9. The best results are obtained at about 4° when the lift component of the total reaction is nearly vertical and it is at this angle that main planes are attached to the fuselage. We must remember however that a given lift value can be obtained with a high rate of airflow and a small angle of attack or a lower rate of airflow and a larger angle of attack up to the angle that produces a maximum lift or the stalling angle. The accident to Bluebird II when attempting to break the water speed record can be directly attributed to "angle of attack". It was anticipated that if the nose of the boat lifted more than 3° at speeds above 300 m.p.h. then uncontrolled flight would occur.

Stalling Angle

10. At small angles any increase of the angle of attack results in an increase of lift, but beyond a certain angle lift begins to decrease. This occurs when the streamlines begin to leave the aerofoil and create eddies and turbulence so destroying the area of reduced pressure above the aerofoil. This is known as the stalling angle. In consequence when an aerofoil approaches its stalling angle a critical airspeed must be maintained or the lift becomes insufficient to support the aerofoil.



Position of lines denote direct of lift.
Length of lines denote magnitude of lift.
Fig. 5. Pressure distribution.

Pressure Distribution

11. The lift of an aerofoil is governed by its shape, angle of attack, air velocity and density but theoretically lift can be represented by lines to show direction whose length indicate magnitude (Fig. 5.).

Centre of Pressure

12. Although the lift produced by an aerofoil consists of a number of small forces acting over a large area, the total force can be considered as a single force acting at a single point. The point where the line of action of a single force would be applied is known as the centre of pressure (C of P).

13. Since lift varies primarily with the rate of airflow and the angle of attack, so the pattern of pressure also varies as does the C of P. Up to the stalling angle the C of P moves forward with an increase of angle of attack so tending to increase the angle further. With a decrease of angle of attack the C of P moves rearward so decreasing the angle of attack. This unstable movement of the C of P is corrected by the tailplane as described later.

Types of Aerofoil

14. The shape of an aerofoil is related to the type and role of the aircraft for which it is designe d For example main planes with a pronounced curvature and a well rounded leading edge as at Fig. 6a. have high lift qualities but are not suitable for high speed aircraft because of the corresponding high drag. Main planes with less camber and a sharper leading edge Fig. 6b. are more suitable for general purpose aircraft; those with little camber and a sharp leading edge as at Fig. 6c. d. can produce an effective lift at high speed with relatively little drag.

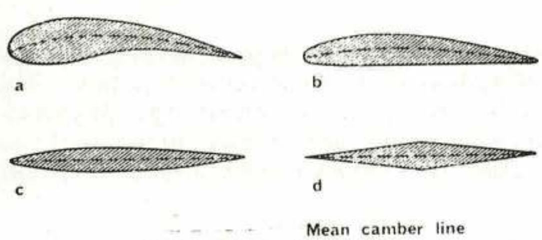


Fig. 6. Types of aerofoil.

Aspect Ratio

15. The plan form of an aerofoil becomes important when the lift of a wing is being considered. The ratio of the span (the distance from wing tip to wing tip) to the chord is termed the aspect ratio and the greater the span in relation to the chord the greater the lift for a given wing area.

16. For high lift aircraft a long narrow wing is preferred although some loss of manœuvrability and constructional difficulties are encountered. Fighter aircraft which cannot be restricted in manœuvrability use a short, rigid, relatively low lift main plane.

17. Smooth airflow is important to the efficiency of an aerofoil but at the wing tips where the increased pressure on the under surface meets the decreased pressure on the upper surface of the wing, eddies form and the air becomes turbulent. It can be shown experimentally that a high aspect ratio wing produces smaller eddies than a low aspect ratio wing. Although many aircraft have square wing tips the effects of wing tip eddies, known as vortices, are greatly reduced if the wing tips are rounded or tapered.

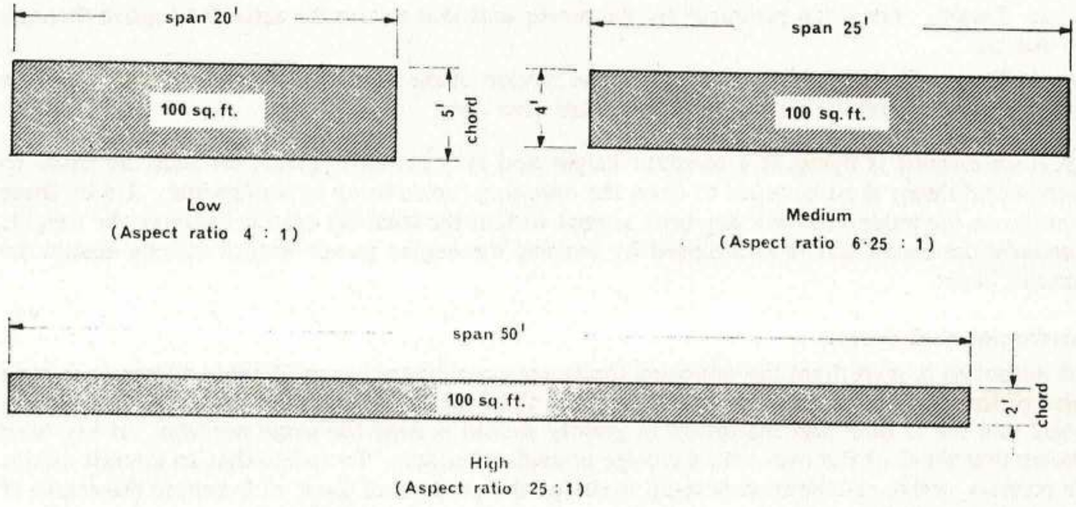


Fig. 7. Examples of aspect ratio.

The Four Forces

18. When an aircraft becomes airborne it is as the direct result of four major forces acting upon its structure and again these can be represented by lines of direction and magnitude (Fig. 8). The forces are:

a. **Lift.** The force that is produced mainly by the aerofoil section of the wings and acts upwards through the centre of pressure, at right angles to the line of flight.

b. **Weight.** The force that is equal to the weight of the aircraft and acts vertically downwards through the centre of gravity and opposes the lift.

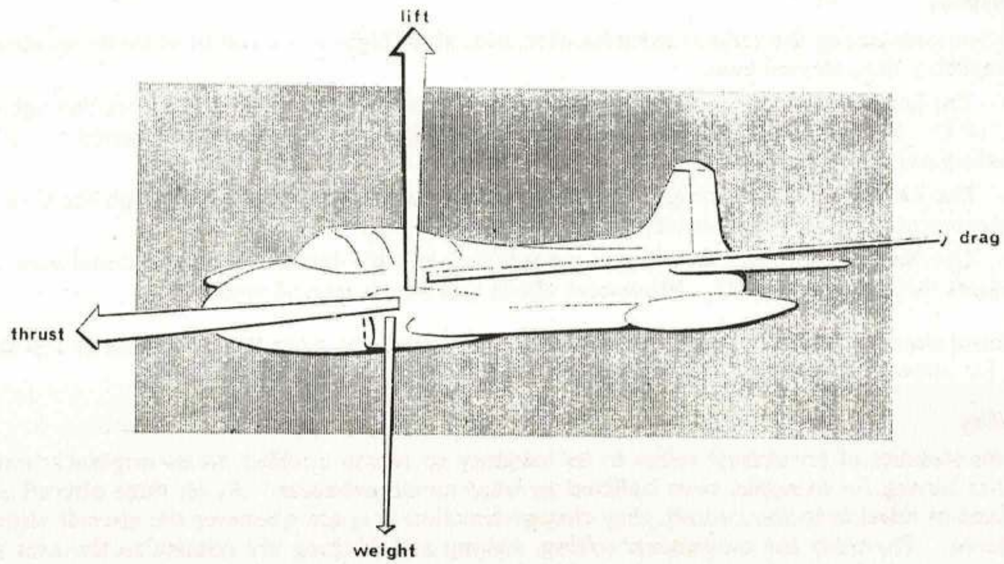


Fig. 8. The four forces.

c. **Thrust.** The force produced by the power unit that causes the aircraft to move through the air.

d. **Drag.** This is the force that resists the motion of the aircraft through the air; it opposes thrust and therefore must act in a rearward direction.

19. If an aircraft is flying at a constant height and at a constant speed, lift must be equal to weight and thrust must be equal to drag, the opposing forces being in equilibrium. Under these conditions the angle of attack has been altered so that the total lift exactly balances the weight; similarly the thrust has been adjusted by varying the engine power until it exactly equals the aircraft drag.

Arrangement of Forces

20. Although in level flight the opposing forces are equal, there is considerable difference in each pair of forces. To be perfectly stable in flight the four forces should act through a common point and the C of P and the centre of gravity should occupy the same position. It has been shown that the C of P moves with a change of angle of attack. To ensure that an aircraft retains its stability within safe limits it is usual to design the position of the C of P behind the centre of gravity, so that lift and weight act together to turn the nose down (Fig. 8).

21. The line of thrust is now arranged so that it acts below the line of drag and a correcting couple is produced to turn the tail down. The main advantage of this arrangement is that should the power (thrust) fail the lift/weight couple will turn the aircraft nose down and put the aircraft into a gliding instead of a stalling attitude. It is now easy to see that the function of the tail plane, as mentioned in para. 13, is twofold:

a. It provides the force necessary to counteract any tendency of the aircraft to pitch whilst in normal flight.

b. It provides the necessary correcting force when any change occurs in the two main couples.

Manœuvres

22. When considering the various attitudes of an aircraft in flight it is usual to relate its movement to imaginary lines termed axes.

a. The **Longitudinal Axis** is a straight line from the nose to the tail which passes through the C of G. Movement about this axis is termed **rolling** and it is sometimes referred to as the rolling axis.

b. The **Lateral Axis** is a straight line passing from wing tip to wing tip through the C of G. Movement about this axis is termed **pitching**.

c. The **Normal Axis** is a line that is perpendicular to the lateral and longitudinal axes and passes through the C of G. Movement about this axis is termed **yawing.**

23. Some changes of aircraft attitude involve movement about more than one axis at the same time for instance a banked turn involves the longitudinal and the normal axes.

Stability

24. The stability of an aircraft refers to its tendency to return unaided, to its original trimmed attitude having for example, been buffeted by local air disturbances. As all three aircraft axes are fixed in relation to the aircraft, they change direction in space whenever the aircraft attitude is altered. Therefore the movements rolling, yawing and pitching are relative to the axes and not to the ground. An aircraft may be stable about two of its axes and unstable about the other, or stable about one axis and unstable about the others.

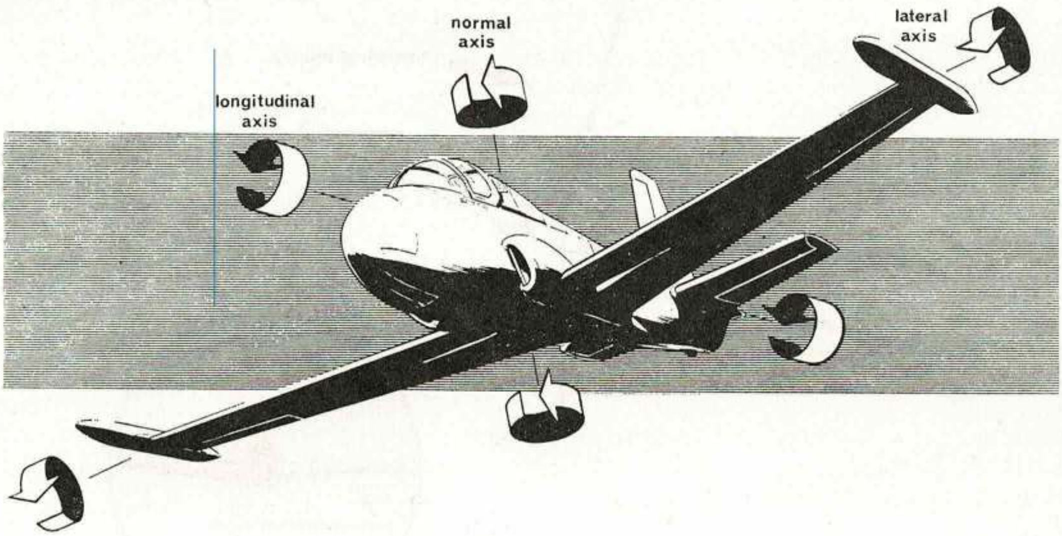


Fig. 9. The axes.

Longitudinal Stability

25. Stability about the lateral axis (longitudinal stability) is assisted by the angle at which the chord of the tail plane is set in relation to the chord of the main plane (longitudinal dihedral angle Fig. 10). Thus while the main plane may be set at a 4° angle of attack the tail plane is set at a very small or even zero angle. Should a gust of wind cause the aircraft nose to lift, the direction of flight does not immediately change. In consequence the angle of attack of both the main plane and the tail plane is increased by the same amount. Though the increased lift of the main plane is far greater than that of the tail plane, the increased lift from the tail plane being applied further from the C of G produces the greater moment, causing the tail to rise and level the aircraft. If the nose of the aircraft falls a similar but in reverse action takes place.

Lateral Stability

26. Stability about the longitudinal axis (lateral stability) is assisted by the upward and outward inclination of the main planes (lateral dihedral angle). If a gust of wind raises one wing the lift and weight forces are momentarily unbalanced and the aircraft will tend to sideslip in the direction of the low wing. Because of the dihedral angle the low wing

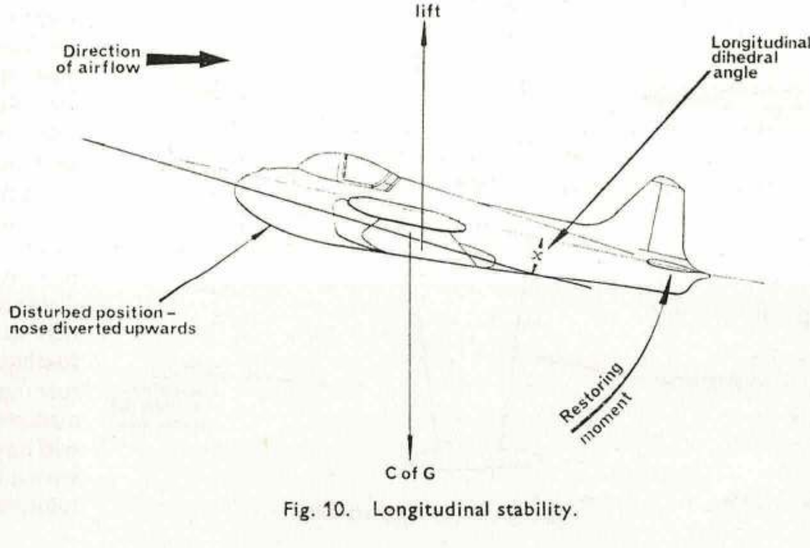


Fig. 10. Longitudinal stability.

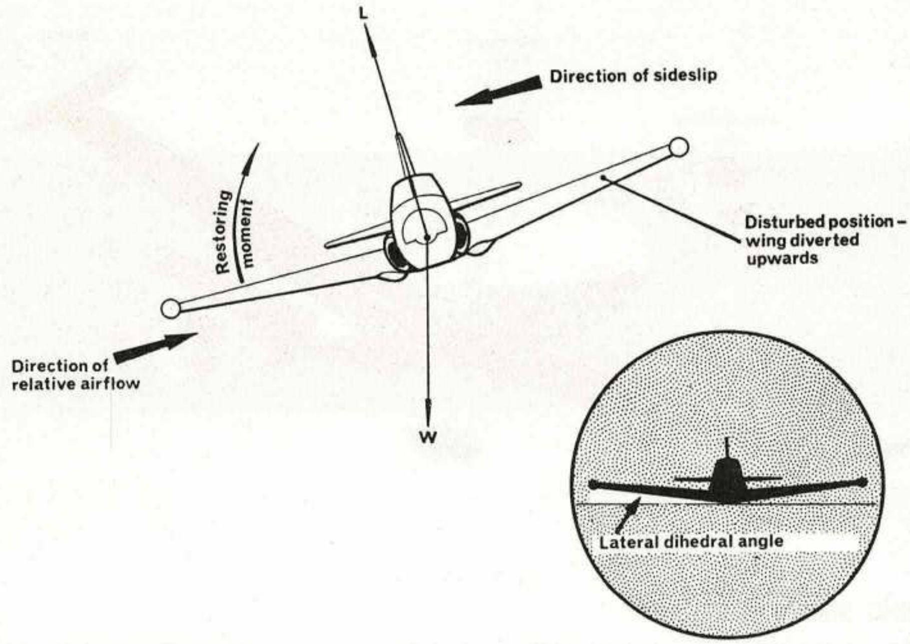


Fig. 11. Lateral stability.

meets the relative air-flow at a greater angle of attack than the high wing, thus the low wing having a greater effective lift the aircraft is restored to an even keel.

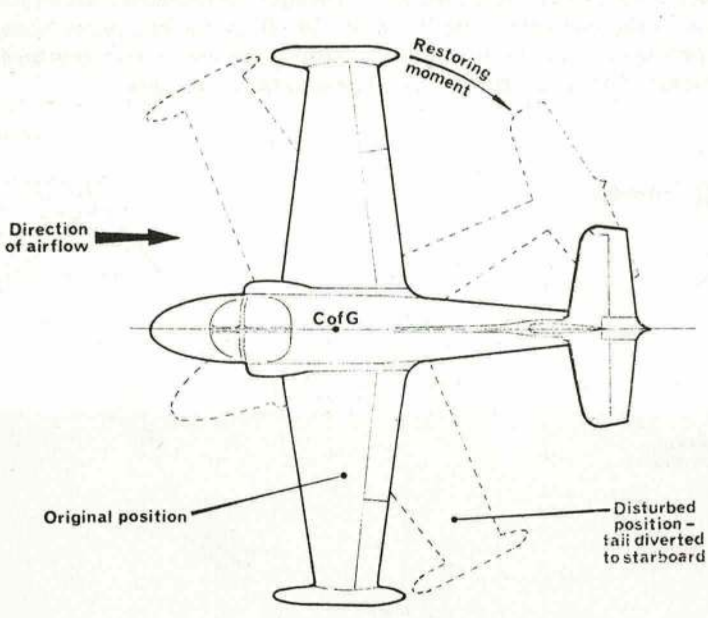


Fig. 12. Directional stability.

Directional Stability

27. Stability about the normal axis (directional stability) is assisted by the aircraft keel surface, that is to say the side surfaces of an aircraft. If a gust of wind forces the tail of an aircraft to one side, the relative airflow meeting the keel surface behind the C of G will cause the aircraft to act like a weathercock and turn into wind, that is to say towards the original line of flight. The distance of the keel surface behind the C of G times the fuselage length produces the turning moment. In general an aircraft with a short fuselage will have a large fin; an aircraft with a long fuselage will have a relatively small fin.

28. In actual practice the three stabilities should be considered together as stability about one axis often affects stability about another axis, e.g. the sideslip necessary to achieve lateral stability may also cause yawing and thus affect directional stability.

Control

29. Control can be defined as the ability of the pilot to move the aircraft about one or all of its axes. Control about the longitudinal axis is known as lateral control. Control about the lateral axis is known as longitudinal control and control about the normal axis is termed directional control.

Lateral Control

30. Control about the longitudinal axis (lateral control) is provided by the ailerons which are hinged to the rear spar of each main plane, near the wing tip. The ailerons which are operated by the control column in the cockpit, are so interconnected that they move in opposite directions thereby assisting each other in causing the aircraft to roll.

31. Movement of the control column to port raises the port aileron and lowers the starboard aileron. This decreases the lift on the port main plane and increases the lift on the starboard main plane, with the result that the aircraft will roll to port. A similar but opposite effect occurs when the control column is moved to starboard. On larger aircraft the sideways movement of the control column is eliminated and a control wheel, which produces a similar effect, is used to actuate the ailerons. The control column or wheel movement is termed "instinctive" control.

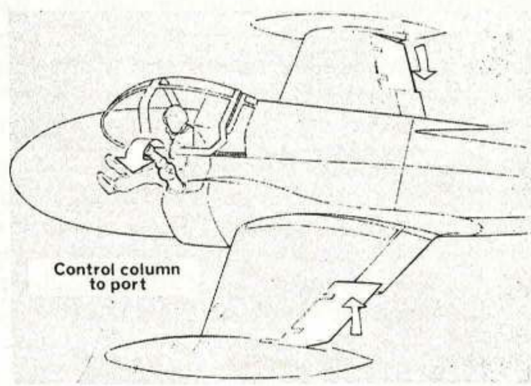


Fig. 13. Port aileron raised—starboard aileron lowered.

Longitudinal Control

32. Control about the lateral axis (longitudinal control) is provided by the elevators which are hinged to the rear spar of the tail plane. The elevators are operated by forward and backward movement of the control column.

33. When the control column is moved forward the elevators are lowered thereby increasing the lift on the tail plane with the result that the aircraft dives. Movement of the control column backwards will raise the elevators thereby decreasing the lift of the tail plane and the aircraft climbs (Fig. 14).

34. Some delta wing aircraft are tailless and have control surfaces (elevons) at the wing tips which combine the function of elevators and ailerons. Movement of the control column fore and aft operates the surfaces as elevators, while turning the control wheel, causes the surfaces to act as ailerons.

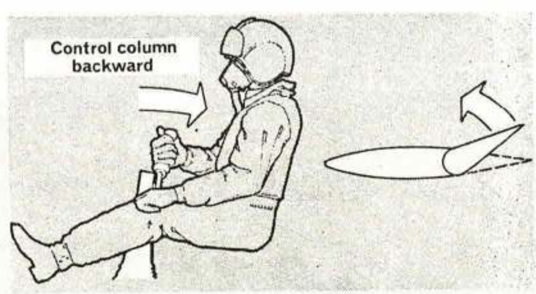


Fig. 14. Elevators raised.

Directional Control

35. Control about the normal axis (directional control) is provided by the rudder which is

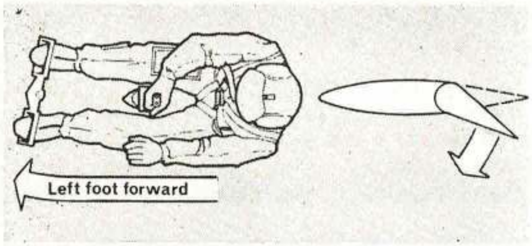


Fig. 15. Rudder to port.

hinged to the rear of the fin or the rear of the fuselage. The rudder is operated by the movement of the rudder bar or pedals in the cockpit.

36. The rudder bar or pedals are operated by the feet and the movement of the left foot forward will turn the rudder to port with the result that the airflow will meet the port side of the rudder and turn the nose of the aircraft to port. A similar but opposite effect occurs with right foot forward which will cause the rudder to turn to starboard (Fig. 15).

Trimming and Balance Tabs

37. An aircraft that is aerodynamically correct should fly straight and true when both hands and feet have been removed from the controls. Few newly built aircraft have this perfect trim and some correcting action must therefore be continuously applied. Such constant effort would soon tire a pilot and to remove such an unnecessary load, trimming tabs are hinged to the trailing edge of the required control surface. Trimming tabs are small auxiliary control surfaces that are off-set to the main surface and provide a permanent bias against an out of trim tendency.

38. A fixed trimming tab can be adjusted only when the aircraft is on the ground. If the aircraft flies starboard wing low the fixed trimming tab on the starboard aileron is adjusted upwards after the aircraft has landed. In further flight the airflow meeting the re-adjusted trimming tab applies a force to the tab that moves the starboard aileron down and the port aileron up, thus increasing the lift on the starboard side and correcting the aircraft trim. Once a fixed trimming tab has been set it should never need to be disturbed unless there is a major component change.

Controllable Trimming Tabs

39. The position of this type of tab can be adjusted in flight by a control wheel in the cockpit. If the aircraft is flying nose heavy the controllable trimming tab on the elevators is adjusted downwards. The airflow meeting the trimming tab forces the elevators upwards so decreasing the lift on the tail plane and correcting the trim of the aircraft (Fig. 16).

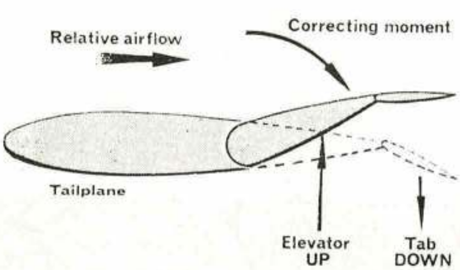


Fig. 16. Correcting nose heavy.

Balance Tabs

40. When an aircraft is flying at high speed a pilot would be required to apply a considerable force to move a control surface against the resistance of the airstream. To assist the pilot to move the controls balance tabs are hinged to the trailing edge of control surfaces, normally the tabs are automatic in operation. When any particular control is moved its balance tab is caused to move in an opposite direction. The airstream meeting the tab applies a force that helps to move the control surface in the desired direction thereby reducing the effort required from the pilot to move the control.

Aerodynamic Balance

41. Although a balance tab will assist the pilot to move a control surface a similar effect can be

achieved by aerodynamic balance. This is done by positioning part of the control surface in front of the hinge line. When the control is moved the airstream then applies a force on the front or balance portion of the control which tends to move the control still further. The control surfaces are only partially balanced so that the pilot may still retain the "feel" of the controls.

Mass Balance

42. At high speeds an aircraft may be subjected to flutter. This is excessive vibration set up by flexure, induced by the air load acting on the airframe structure. Flutter is very dangerous as it increases in intensity with increase in speed so that ultimately, if the speed is not reduced, the aircraft will break up in the air.

43. As would be expected greatest flexure occurs at those points furthest from the aircraft C of G. Control surfaces are therefore mass balanced. This consists of adding weights, usually lead, in front of the hinge line and generally inside the control surface. The amount of weight added is important and is sufficient to ensure that flutter will not occur in the vicinity of the control surface within the normal speed range of the aircraft (Fig. 17).

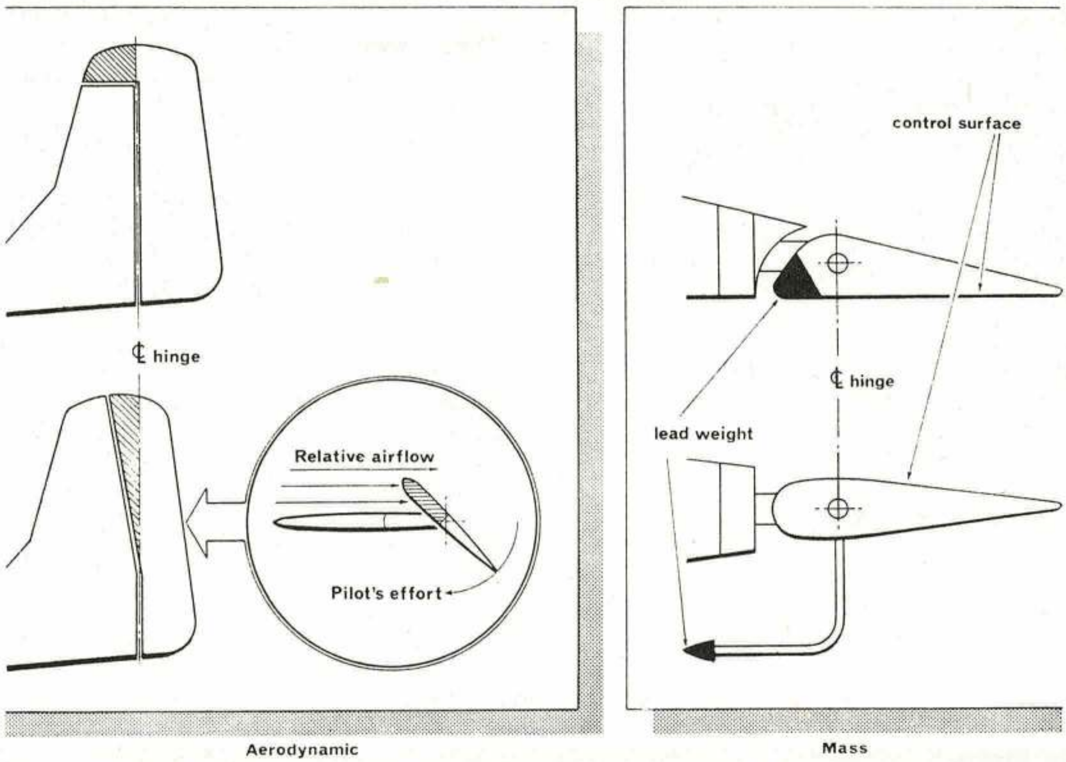


Fig. 17. Types of balance.

Trailing Edge Flaps

44. Trailing edge flaps are hinged to the rear spar inboard of the ailerons and are usually hydraulically operated from the cockpit. When operated they move downwards to increase the camber and sometimes the area of the main planes, thereby increasing both lift and drag. Flaps are used to give the aircraft a slower landing speed and a steeper gliding angle and are

sometimes used to give a shorter take-off. Various types of flaps are in use including the following:

a. **Plain Flap.** The plain flap consists of the whole rear portion of the main plane which when lowered increases both lift and drag.

b. **Split Flap.** This flap consists of the lower surface only of the rear portion of the main plane. Thus the upper surface of the main plane remains unchanged when the flap is lowered. Depending upon the angle selected, this flap gives greater increase in lift than the plain flap.

c. **Extension or Fowler Flap.** This flap is similar to the split flap but in operation the extension flap moves downwards and backwards thus increasing both the effective chord and the angle of attack. Its main purpose is to increase lift.

d. **Slotted Flap.** The hinge line of this type is inset so that as the flap is lowered a gap or slot is formed between the main plane and the flap. Air passing through the slot maintains the required smooth airflow over the upper surface of the trailing edge that permits an increase of lift to a greater angle than a plain flap.

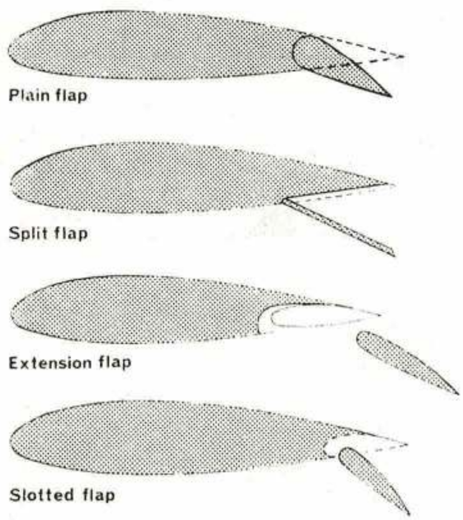


Fig. 18. Trailing edge flaps.

Wing Fences

45. A spanwise movement of the airflow occurs on main planes with swept-back leading edges and with an increase of angle of attack the turbulence at the wing tips increases, thereby decreasing the effectiveness of the ailerons. This unsatisfactory feature can be counteracted by the fitting of wing fences to the main planes (Fig. 19).

46. The fences are small chordwise metal strips a few inches in height fitted on the upper surface of the main planes. They may extend from leading to trailing edge or over only part of the chord. On some main planes the fences may even be continued around the leading edge and for a short distance on the lower surface of the main plane.

47. Wing fences relieve the wing tip stalling tendency either by inducing the stall inboard of the tip or by restricting the spanwise movement of the airflow or by a combination of both.

Air Brakes

48. Air brakes, sometimes called spoilers, are an integral part of an airframe designed to produce drag when required. They may be situated at the rear of the fuselage or on top of and/or underneath the main planes. They usually consist of flat or contoured plates which can be operated from the cockpit and turned at right angles to the airstream. On medium and high speed aircraft the brakes are often used to reduce speed before turning, manœuvring or landing; on high speed aircraft particularly they may be used to prevent the aircraft exceeding a predetermined speed. Aircraft that have high landing speeds are fitted with brake parachutes

to reduce the length of the landing run so obviating the necessity to increase the aircraft wheel brake size out of all proportion.

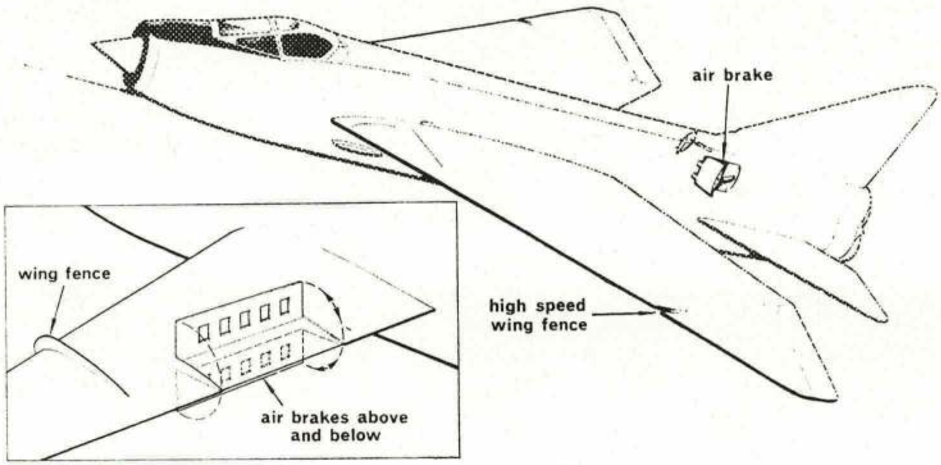


Fig. 19. Typical examples of wing fences and air brakes.

Leading Edge Slats

49. To delay wing stall and gain extra lift and control at low flying speeds, a small auxiliary aerofoil slat may be attached to the leading edge of the main planes in such a manner that an air slot is formed between them. Thus any turbulence that may form, or tend to form, on the top surface of the main plane is smoothed out by the air flowing through the slot. For example, where the stalling angle of attack of a main plane without slats is 16° the angle may be increased to about 26° by the fitting of slats.

50. The slats may be spring loaded to the closed position and automatically move to open the slots. For example as a main plane approaches the stall angle the C of P of the stall moves forward and raises the slat to permit a stream of air to pass between the slat and the main plane.

51. When the aircraft reverts to a more normal attitude the C of P moves backward and the spring loaded mechanism pulls the slat to the slot closed position. On some aircraft the slats are operated from the cockpit in conjunction with the flaps. Another method of producing a similar result is to have "built in" slots in the wing tips just behind the leading edge.

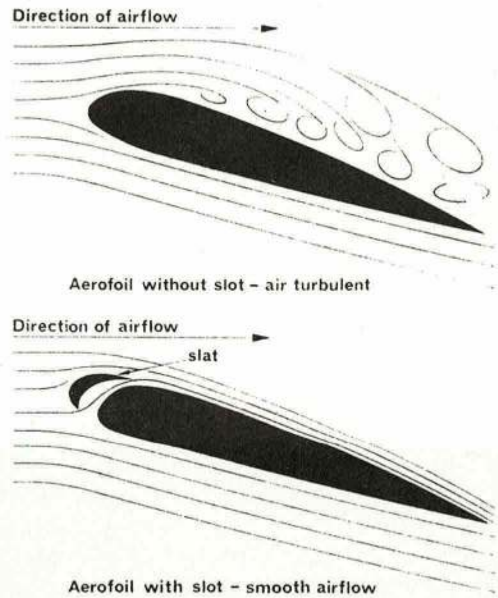


Fig. 20. Action of automatic slat at normal stalling angle.