

PART 1 : SECTION 1

CHAPTER 4

LIFT

Introduction

1. The lift of an aerofoil is the upward reaction obtained by changing the direction of a moving stream of air. Moving air, having both density and velocity, possesses energy. The problem in heavier-than-air machines is to obtain some means of using this energy to produce lift.

2. If a smooth stream of air disappears behind a screen B (Fig. 1(a)) and emerges at C with the same velocity as at A, then behind the screen either no force has been applied to the fluid or the net effect of any forces which may have been applied has been nil. If, however, the velocity at C is not the same as at A, then a force has been applied to cause this change. As shown in Fig. 1(b) the velocity at A is horizontal while that at C is inclined downwards. Irrespective of the exact mechanism used to bring about this deflection it can be stated that, behind the screen, a downward force has been applied to the air stream, and consequently there must have been an accompanying reaction by the air on whatever caused the downward motion. It is immaterial what means is employed to change the velocity of the free air stream: once it is changed, then the reaction called lift is present.

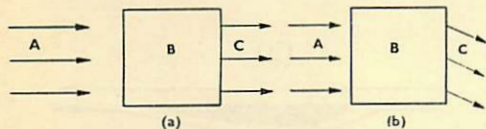


Fig. 1. Downwash and Lift

3. The easiest method of producing this deflection, which is known as *downwash*, is to place a flat plate in the airflow inclined at a suitable angle to change the direction. However, a more efficient means of producing the required change in direction is the curved section seen on the wings of aircraft and birds, on the blades of propellers, and on the rotor of helicopters.

4. The aerodynamic principles whereby this curved surface implements its purpose are detailed in subsequent paragraphs.

Aerofoil Definitions

5. In order to clarify the explanations which follow, certain basic terms relating to the wing

are defined below and illustrated in Fig. 2.

(a) *Chord Line*. The chord line of the aerofoil is the straight line joining the leading edge to the trailing edge. It is used as an arbitrary reference line when measuring the angular position of the wing in relation to the airflow.

(b) *Mean Camber Line*. A line joining the leading and trailing edges of the wing, equidistant from the upper and lower surfaces of the aerofoil. If the line is curved, the aerofoil is said to be cambered.

(c) *Angle of Attack*. The angle between the chord line of the wing and the oncoming airflow.

(d) *Angle of Incidence*. The angle between the chord line of the aerofoil and the fore-and-aft datum line of the aircraft, and thus entirely arbitrary. The angle of incidence is usually fixed by the rigid attachment points which hold the wing and fuselage together but on a few types of aircraft it is, to some extent, controllable in flight.

(e) *Thickness/Chord Ratio*. The t/c ratio is a measure of the aerodynamic thickness of the aerofoil; it corresponds to the fineness ratio of a body, mentioned in the chapter on drag. The t/c ratio is usually given as a percentage and varies between about 18 per cent. and 5 per cent. A t/c ratio of, say, 10 per cent. would mean that the thickness of the section was 10 per cent. of the chord. A wing having a t/c ratio of 10 per cent. and a chord of 30 ft. would have a corresponding maximum thickness of 3 ft.; with a chord of 10 ft. the maximum thickness would be 1 ft.; aerodynamically, both wings are equally thin.

(f) *Wing Loading*. The all-up weight (A.U.W.) of the aircraft divided by the wing area, *i.e.* the amount of the total weight carried by unit area of the wing. It is usually given in lb. per square foot.

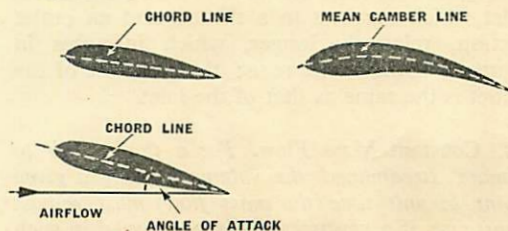


Fig. 2. Physical Characteristics of Aerofoils

Bernoulli's Theorem

6. Daniel Bernoulli, an early Italian physicist, discovered certain properties relating to fluids in movement. These were expressed in the mathematical statement that the total energy in a moving fluid or gas is made up of three forms of energy—the energy due to the height or position (the potential energy), the energy due to pressure, and the energy due to movement (kinetic energy)—and that in the streamline flow of an ideal fluid the sum of all these is constant.

7. When considering the flow of air the potential energy can be ignored; the statement can therefore be modified, for all practical aerodynamic purposes, by saying that the kinetic energy plus the pressure energy of a smooth flow of air is always constant. Thus, if the kinetic energy is increased, the pressure energy drops proportionately so as to keep the total energy constant.

8. A simple example of this law is given by a closed tap which is storing water at a certain total energy. If a small hole is drilled into the pipe, the pressure energy, which is at a maximum, will cause a jet of water to spurt from the hole, the length of the jet being determined by the pressure energy. If the tap is opened slightly, the water begins to move and a proportion of the total energy changes to kinetic energy; the more the tap is opened, the greater the rate of movement and the greater the proportion of kinetic energy. At the same time the pressure energy falls in proportion; this can be seen by the diminishing length of the jet issuing from the leak. When the tap is fully open the kinetic energy is at its peak, while the pressure energy and the length of the jet will have fallen to their lowest value. During the whole operation the total energy in the pipeline has been constant.

Venturi Tube

9. A practical application of Bernoulli's theorem with which the pilot should be familiar is the venturi tube, sometimes called a convergent/divergent duct (Fig. 3). The venturi tube has an inlet which narrows to a throat, and an outlet section, relatively longer, which increases in diameter towards the rear; the diameter of the outlet is the same as that of the inlet.

10. **Constant Mass Flow.** For a flow of air to remain streamlined the volume passing a given point in unit time (the mass flow) must remain constant; if a venturi tube is positioned in such an air stream then, for the air to remain stream-

lined, the mass flow through the venturi must remain constant. To do this and still pass through the reduced cross-section of the throat the speed of flow through the throat must be increased. In accordance with Bernoulli's theorem this brings about an accompanying pressure drop.

11. As the cross-sectional area is narrowed progressively, it follows that the increase in speed and the reduction in pressure are progressive; the highest and lowest values respectively occur at the point where the restriction is greatest.

12. Fig. 3(a) shows a diagrammatic flow of streamlines through a venturi tube. If the walls of the venturi are drawn further apart, as shown in Fig. 3(b), the streamlines immediately adjacent to the wall follow closely the contour of the wall. Further away from the wall the streamlines become less and less curved or deformed. In the central part of the flow the streamlines are straight.

13. Moving the walls still further apart, until there is no interaction between the two, results in the flow pattern shown in Fig. 3(c). Here there

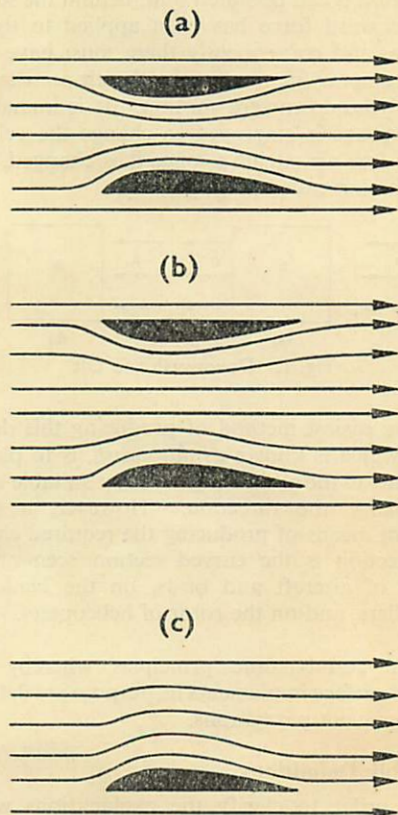


Fig. 3. Development of a Wing from a Venturi Tube

is a curved surface with the adjacent streamlines closely following the contour; at a comparatively short distance away from the upper surface the streamlines are those of the free air stream, unaffected by the presence of the curved walls. This is the flow pattern over a typical wing, in this case at zero angle of attack.

14. Upstream from the surface, where the flow is again free and undisturbed, the streamlines are equally spaced, indicating a steady speed and pressure. Directly above the curved wall the streamlines are closer together, indicating an increase in speed and a decrease in pressure. The cross-section through a wing, known as an *aerofoil section*, is shaped so that the upper surface has this accelerating effect on the airflow with the accompanying drop in pressure. Therefore when a wing is moving through the air, the pressure on the upper surface is slightly less than atmospheric pressure. If the angle of attack is such that normal atmospheric pressure is present on the under surface of the wing, then all the lifting force is due to the pressure on the upper surface being less than atmospheric.

15. Para. 9 stated that a venturi tube is known also as a convergent/divergent duct. The reverse shape is a divergent/convergent duct. If a body of this shape is placed in a streamline flow, the effect on the airflow through it is exactly the opposite to that produced by a venturi. The mass flow must remain constant through the duct and to do this the speed must decrease, with an accompanying pressure rise.

16. In flight the wing meets the airflow at a small angle of attack. When the air stream meets the inclined under surface it exerts a pressure and consequently, again in accordance with Bernoulli's theorem, the speed decreases. This is shown in a wind tunnel by a diverging in the spacing of the streamlines under the wing.

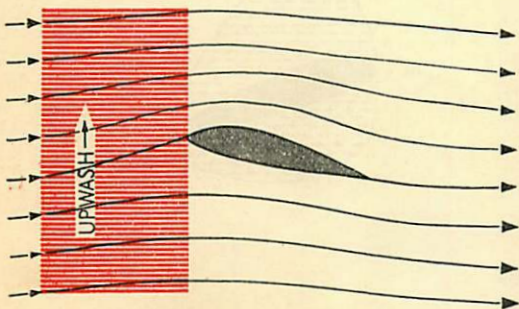


Fig. 4. Upwash Ahead of an Advancing Wing

17. This lifting effort on the lower surface can be improved by the use of under-camber, *i.e.* a concave lower surface. In this way a divergent/convergent duct effect is obtained from the under surface which causes a greater decrease in the speed of the air stream and a greater increase in pressure. This type of aerofoil is unsuitable for all but the lowest speeds, for reasons which will be given later.

18. If the pressure on each square inch of the under surface is atmospheric pressure of 14.7 lb./sq. inch, and if the pressure of each square inch of the upper surface is, say, 14.54 lb./sq. inch, then there is a pressure difference of .16 lb. per square inch acting upward. This pressure of .16 lb. per square inch equals 23.0 lb. per square foot, a rather low *wing loading*. When the angle of attack is about 10° , the pressure rise below causes about 30 per cent., and the pressure drop above the wing about 70 per cent. of the total lifting force. Notice that the proportion varies with the angle of attack. Fig. 5 shows the pattern of the streamlines over an aerofoil at a fairly high angle of attack at subsonic speed.

19. **Upwash.** Fig. 4 shows that, in advance of the wing, the streamlines of air curve upwards towards the top surface. Upwash, as this is called, is an inherent feature of any surface which is giving lift and exists because air always tends to flow towards an area of low pressure. The deeper the low-pressure region the greater the amount of upwash.

Distribution of Pressure about the Wing

20. The pressures around the wing of an aircraft in flight can be determined comparatively simply, either in free flight or in a wind tunnel, by tapping selected points of the wing and measuring the pressures. Fig. 4A shows an aerofoil which has had a series of smallappings made in a chordwise direction over the wing. Each of these small holes is connected via a rubber tube to a single glass tube in a battery of glass tubes (a manometer). The tubes are filled with an easily visible liquid so that initially the levels in the whole battery of tubes are equal. If the prepared wing is placed in an air stream at a selected angle of attack, then the pressures picked up by the variousappings will be transmitted to the liquids in the respective tubes, the level in each tube adjusting itself to the pressure experienced. The differences in level can then be measured and expressed in terms of pressure.

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A.P. 129, VOL. 1, PART 1, SECT. 1, CHAP. 4

21. **Centre of Pressure.** Fig. 5 shows typical pressure distributions around a wing at various angles of attack. Over the first half of the upper surface there is a marked decrease in pressure which increases to atmospheric pressure at the trailing edge. Over the lower surface there is a pressure rise which is not as marked as the pressure drop above. The pressure rise below the

wing is, again, most pronounced over the first half of the chord. The total reaction of the pressures acting along the upper and lower surfaces can be represented by a single resultant having magnitude, direction, and position. The position at which the resultant operates at a given angle of attack is known as the *centre of pressure*.

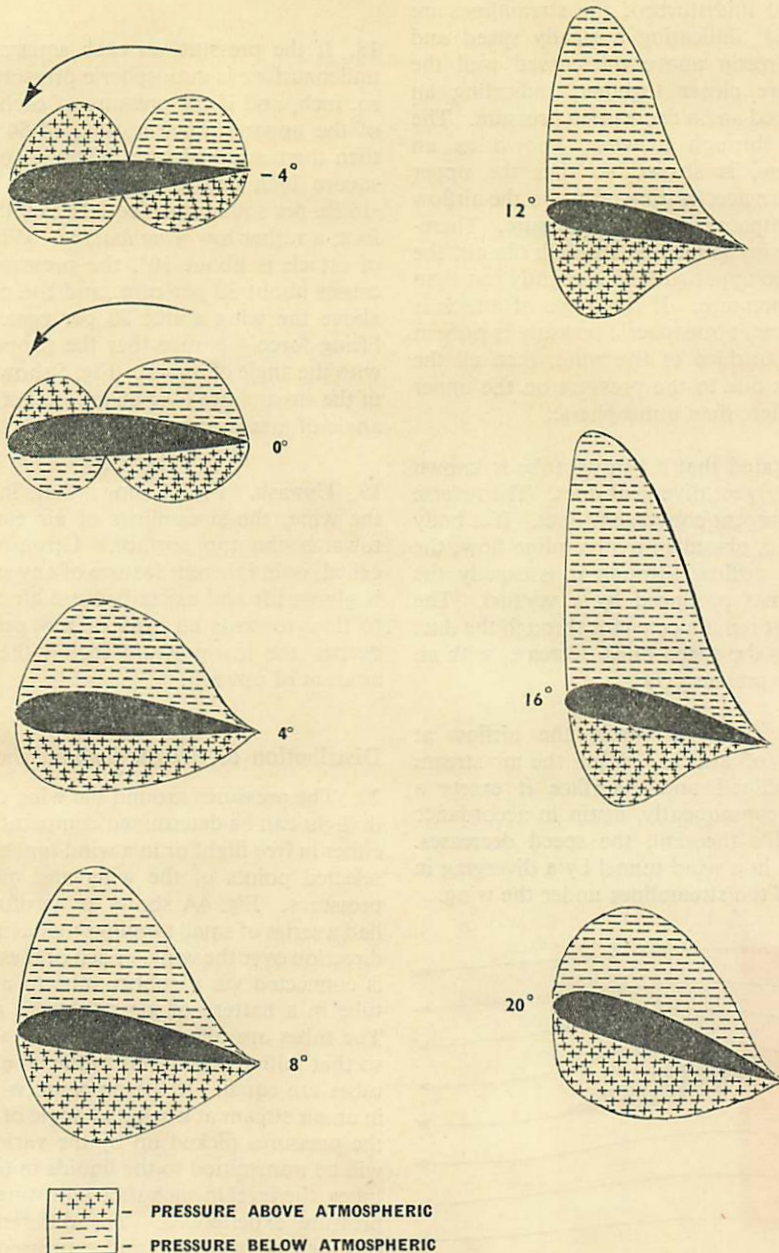


Fig. 5. Typical Pressure Distribution Around a Wing at Various Angles of Attack

Lift Coefficient (C_L)

22. When several wings of the same geometrical shape and area but with different aerofoil sections are compared at a given angle of attack and air speed, the lift obtained from each wing varies, the exact amount of lift depending on the aerofoil section used. Generally, at subsonic speeds at a given angle of attack, the greater the camber or curvature of the upper surface the greater the amount of lift obtained from a given wing: conversely, the flatter the camber and the thinner the wing the less is the lift. The difference is due to the greater accelerating effect on the air stream of pronounced camber, resulting in a larger reduction in pressure. The measure of the lifting effectiveness or power of a wing under a given set of conditions is its *lift coefficient* or C_L . The C_L is not constant but varies with the angle of attack. Furthermore, various aerodynamic aids can be used to increase the C_L and thus raise the lifting effectiveness of a wing. All else being equal, the higher the C_L the lower is the minimum speed at which a given wing can produce a required lift; these factors will be considered in greater detail in Chapter 5, "Stalling". The formula for calculating the lift is:

$$\text{Lift} = C_L \frac{1}{2} \rho V^2 S$$

Since the expression $\frac{1}{2} \rho V^2 S$ applies to *all* aerodynamic forces, it is sufficient, when considering increases or decreases of lift *under a given set of conditions*, to refer to the increase or decrease of the lift coefficient alone. Thus an increased C_L implies an increased lift, and vice versa.

23. When a wing/aerofoil combination is placed in an air stream at a given angle of attack, and the speed of this stream is then progressively increased, the lift increases in proportion to the square of the speed as shown by the lift formula, the amount of lift being determined by the C_L at that angle of attack. At some high subsonic speed the rate at which the lift has been increasing, in accordance with the V^2 law, begins to fall appreciably. This effect is caused by the compressible nature of the air which, although negligible at low speeds, begins to play an important part at the highest subsonic speeds. Compressibility, as this is called, brings with it a reduction in the C_L and hence a falling off in the rate of increase of lift, owing to fundamental changes in the nature of the airflow.

Measurement of Forces in Flight

24. To simplify this explanation it is best to consider a wing of a certain aerofoil section and of rectangular shape placed in an air stream which is moving at a constant, low subsonic speed. The

wing is mounted on a balance so that the angle of attack can be changed and the resulting forces measured by weighting the balance to maintain equilibrium.

25. This method of determining the performance of an aerofoil is unrealistic, because in practice there is a relationship between the angle of attack and the air speed which results in a change of air speed when the angle of attack is changed, and vice versa; this effect will be covered later in the chapter on stalling. For the purposes of comparing different aerofoils, however, the constant air speed method is convenient and accurate.

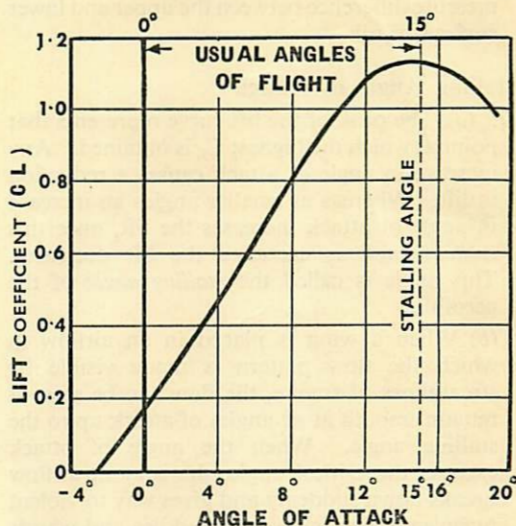


Fig. 6. Variation of Lift with Angle of Attack

Variation of Lift Coefficient with Angle of Attack

26. (a) Fig. 6 is a graph showing the variation of lift coefficient with angle of attack. This graph contains a number of important points. The first of these is that when the angle of attack is 0° there is a positive C_L and therefore a positive lift. This is a property of all cambered aerofoils; a flat plate or symmetrical aerofoil has no lift when the angle of attack is zero. The cambered aerofoil, however, continues to give lift at this angle of attack because there is still a pressure difference, acting in the right direction, between the lower and upper surfaces.

(b) Between 0° and 12° the line of the graph is straight, showing that there is a steady increase in lift. Above 12° , although the lift still increases for a few degrees, the rate of increase is reduced, and eventually the graph forms a

peak. For this aerofoil the angle of attack at which the peak forms is about 15° . If the angle is increased the lift begins to decrease, and the line of the graph curves downwards.

(c) The angle of attack at which the peak occurs varies with the aerofoil section; not all aerofoils have a peak lift stall at an angle of 15° but any differences will be small—not more than 1 or 2 degrees in either direction—provided that the same plan form is used in each case.

(d) The angle of attack at which no lift is obtained is that at which the net effect of the aerofoil on the airflow past it is nil, *i.e.* where there is no downwash or upwash and the total pressure difference between the upper and lower surfaces is nil.

Stalling Angle of Attack

27. (a) The peak of the lift curve represents that point at which the highest C_L is obtained. Any increase in angle of attack causes a reduction in lift. Whereas at smaller angles an increase in angle of attack increases the lift, once this *critical angle* is exceeded the lift decreases. This angle is called the *stalling angle* of the aerofoil.

(b) When a wing is placed in an airflow in which the flow pattern is made visible by streamlines of smoke, the flow can be seen to remain smooth at all angles of attack up to the stalling angle. When the angle of attack exceeds the critical angle, the smooth airflow breaks down suddenly and gives way to violent turbulence characterized by eddies and whorls of air.

(c) The airflow may be disrupted to such an extent that air from the lower surface of the aerofoil flows around the trailing edge and moves up the top surface towards the leading edge. This disruption of the airflow is called turbulence or burbling.

(d) From Fig. 5 it can be seen that just before the stall a marked low pressure region has built up over the leading edge of the upper surface. At the stall this region collapses when the airflow becomes turbulent; this accounts for the sudden loss of lift. Over the remainder of the aerofoil, however, the pressure distribution remains much the same, and although a substantial loss of lift occurs the aerofoil still produces lift.

(e) *Stall Warning.* Although the airflow becomes completely turbulent only when the critical angle is reached, the approach of an impending stall is often conveyed to the pilot by the effect of local breakdowns in the airflow

at some angle of attack close to, but lower than, the stall. These local breakdowns cause turbulence which, as it strikes the aircraft structure and flows over the control surfaces, produces vibration and buffeting which can often be felt distinctly. The degree of buffet varies widely between aircraft; on some there may be none at all while on others it may be strong. Furthermore, the buffet may start at some 10 knots before the stall or at some speed very close to the stall. The intensity of the buffeting usually grows stronger as the stall is approached and the turbulence spreads. Stall warning is a desirable requirement of all aircraft and, in its absence, some aircraft are fitted with electro/mechanical devices to convey the warning in the form of a visual or audible signal.

(f) A more detailed approach to stalling is made in the next chapter.

Variation of Drag with Angle of Attack

28. Fig. 7 shows that total drag varies steadily with change of angle of attack, being least at small positive angles and increasing on either side. The rate of increase becomes marked at angles of attack above about 12° , and after the stall it increases at a greater rate. The sudden rise at the stall is caused by the turbulence resulting from the breakdown of streamline flow.

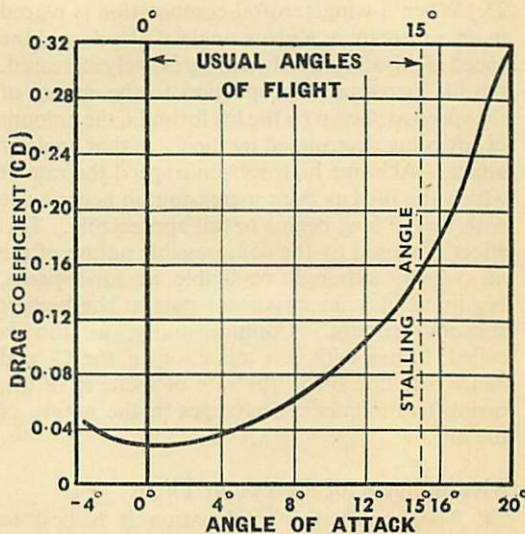


Fig. 7. Variation of Drag with Angle of Attack

Variation of Lift/Drag Ratio with Angle of Attack

29. (a) It will be apparent that for a given amount of lift, it is desirable to have the least possible drag from the aerofoil. It has been shown from the lift curve that the greatest lifting effort is obtained at an angle of about 15° and, from the drag curve, that least drag occurs at an angle of attack of about 0° . Neither of these angles is satisfactory, as the ratio of lift to drag at these extreme figures is low. What is required is the maximum lifting effort compared to the drag at the same angle ; *i.e.* the highest lift/drag ratio (L/D ratio).

(b) The L/D ratio for an aerofoil at any selected angle of attack can be calculated by dividing the C_L at that angle of attack by the corresponding C_D . In practice the same result is obtained irrespective of whether the lift and drag or their coefficients are used for the calculation.

(c) Fig. 8 shows that the lift/drag ratio increases rapidly up to an angle of attack of about 4° at which point the lift may be between 12 to 20 times the drag, the exact figure depending on the aerofoil used. At larger angles the L/D ratio decreases steadily, because even though the lift itself is still increasing the proportion of drag is rising at a faster rate. At the stall the L/D is about 4 and at an angle of attack of about 90° it is nil.

(d) One important feature of this graph is the indication of the angle of attack for the highest L/D ratio ; this angle is one at which the aerofoil gives its best all-round performance. At a higher angle the required lift is obtained at a slower and hence uneconomical speed ; at a lower angle it is obtained at a higher and also uneconomical speed. This point is covered in greater detail in the next chapter.

Movement of the Centre of Pressure

30. (a) It has been stated that the *total reaction* of all lifting forces has magnitude, direction, and position ; the point of intersection of the line of direction with the chord (*i.e.* the position) being called the *centre of pressure*.

(b) Fig. 9 shows the movement of the centre of pressure of a cambered aerofoil at various angles of attack ; this aerofoil having a large C.P. movement. Symmetrical aerofoils have virtually no C.P. movement over the working range of angles of attack at subsonic speeds. Fig. 10 shows the effect of changes in the angle of attack on C.P. position and also on the direction and magnitude of the total reaction.

(c) At small angles of attack the total reaction is comparatively small ; its direction is upward and rearward from the vertical with reference to the free air stream, and the centre of pressure lies at about the 50 per cent. chord point. At medium angles the total reaction is larger ; its direction has changed to a more nearly vertical one with reference to the free air stream, and the centre of pressure has moved forward to around 30 per cent. to 40 per cent. of the chord, aft of the leading edge. At high angles of

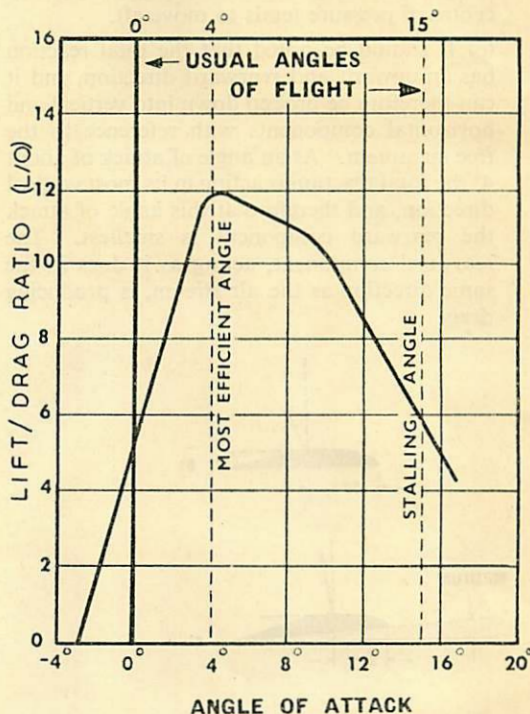


Fig. 8. Variation in L/D Ratio with Angle of Attack

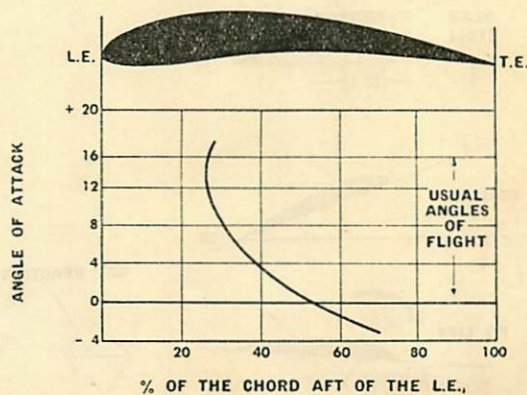


Fig. 9. Movement of the Centre of Pressure with Angle of Attack

attack, close to the stall, the total reaction is larger still but its direction is now inclined further rearward from the vertical, and its centre of pressure has moved to its most forward position—about 20 per cent. to 25 per cent. of the chord aft of the leading edge.

(d) Any increase in the angle of attack beyond the stalling point causes a decrease in the magnitude of the total reaction; its inclination rearward from the vertical with reference to the free air stream becomes still larger and the centre of pressure tends to move aft.

(e) It should be noted that the total reaction has an upward and rearward direction, and it can therefore be broken down into vertical and horizontal components with reference to the free air stream. At an angle of attack of about 4° the total reaction is acting in its most vertical direction, and therefore at this angle of attack the rearward component is smallest. The rearward component, acting as it does in the same direction as the air stream, is producing drag.

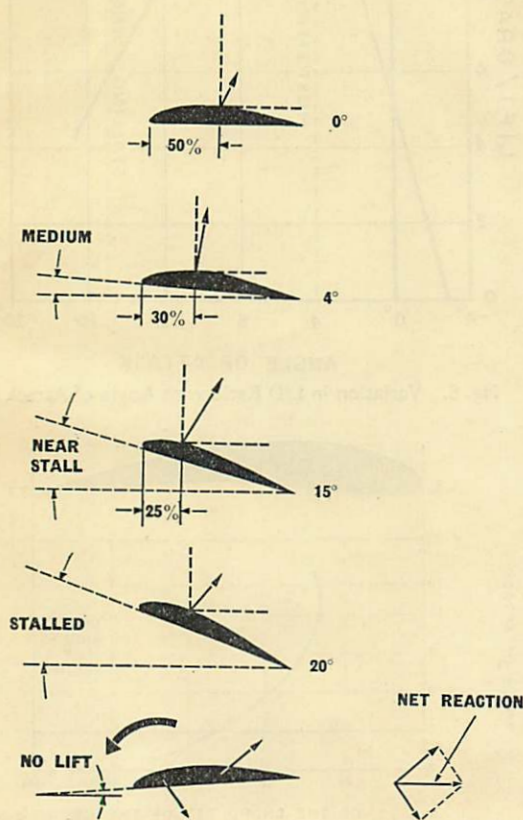


Fig. 10. Variation of Centre of Pressure and Total Reaction with Angle of Attack

(f) Starting from this angle of attack and then decreasing, the total reaction becomes smaller, its direction moves further aft from the vertical, and the centre of pressure moves rearward towards the trailing edge. At the angle of attack for zero lift, which may be at about -4° , depending on the amount of camber of aerofoil under test, the centre of pressure has moved back to a position where the total reaction cannot now be shown by a single force. At the front of the aerofoil the total force is downward and rearward; at the rear of the aerofoil the total force is upward and rearward. The net effect of these split forces is to produce a resultant force acting only in a horizontal direction, *i.e.* there is no vertical component and therefore no lift.

(g) This does not give the complete picture, because when considering the aerofoil as a whole there is as much upward as there is downward pressure. At the front of the aerofoil, the pressure is downward and at the rear it is upward. Thus, although the resultant is acting in the direction of the air stream and giving no lift, there is a couple, tending to force the leading edge down and the trailing edge up, *i.e.* producing a nose-down tendency. This is usually termed a pitching moment.

(h) At angles of attack more negative than that described in sub-para. (g) the total reaction is once more a single force, but now it is acting rearward and downward with the centre of pressure well aft, having moved forward slightly. As the angle becomes still more negative the resultant becomes larger, its direction more downward, and the centre of pressure moves further forward. Thus roughly the same sequence of events occurs as that found at positive angles of attack.

Airflow Around the Wing

31. So far the airflow over a cross-section of the wing has been considered, *i.e.* the flow in two dimensions only, but before these results can be applied to the complete wing an allowance must be made for the effect of the wing tips. The wing tips give rise to a spanwise component in the airflow, and the problem therefore becomes three-dimensional. If a flat plate is drawn through water, it can be seen that there is a marked flow around the tips of the plate from the lower surface towards the upper surface, and that a vortex forms at each tip. A wing which is producing lift acts in the same way as this plate.

32. As the air approaches the wing the streamlines are parallel and, while in level flight,

horizontal. Just before reaching the wing, the airflow changes direction upwards to form a region of upwash; it leaves the wing in a direction different from that of the free air stream to form the downwash.

33. This simple picture is modified when the complete pressure distribution over the wing, and its effect on the two-dimensional flow, is brought into the picture. The pressure distribution envelope, when seen from the front of the aircraft, takes the approximate form shown in Fig. 11; the precise shape of the envelope depends on the angle of attack and on the plan form of the wing.

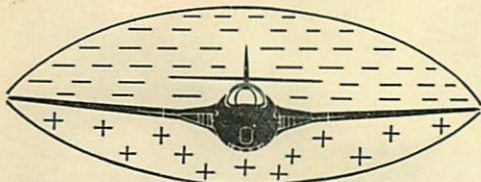


Fig. 11. Typical Pressure Distribution Envelope

Wing-Tip Vortices

34. The pressure difference between the upper and lower surfaces of the wing tips causes air to spill around the tips from the high-pressure region below the wing to the low-pressure region above. Because the main airflow is moving past the tips, the overall effect is the formation of a spiral flow or vortex from each tip, the direction of rotation of the vortices being inwards, towards the fuselage. The vortices are most pronounced at high angles of attack, when the pressure difference is at its maximum. Under certain conditions, the pressure at the core of a strong vortex may drop low enough to cause condensation of the water vapour content of the air. This results in visible streams of vapour originating from each wing tip called wing-tip condensation trails.

35. Bearing in mind the direction of rotation of the vortices, it can be seen that they induce an upward flow of air outside of the span (which does not affect the wing) and a downward flow behind the trailing edge. This induced downwash has nothing in common with the downwash necessary to produce lift. It is, in fact, the source of induced drag. The greater the size and strength of the vortices and the consequent downward component on the net airflow over the wing, the greater the induced drag effect becomes. The lift component of the total reaction has been said to act at right angles to the free air stream. However, since the *net* direction of the free

air stream has had a downward component induced by the wing-tip effects, the lift vector, still acting at right angles to the free stream, is tilted backwards and thus has a rearward component (Fig. 12). The size of the rearward component is proportional to the angular amount of the induced downwash and, in turn, to the induced drag. To sum up, if the wing-tip vortices increase, they induce an increased downwash over the wing; this results in a greater rearward tilt of the lift vector, the horizontal component of which is proportional to induced drag. Fig. 13 gives an idea of the size and shape of typical vortices at a high angle of attack.

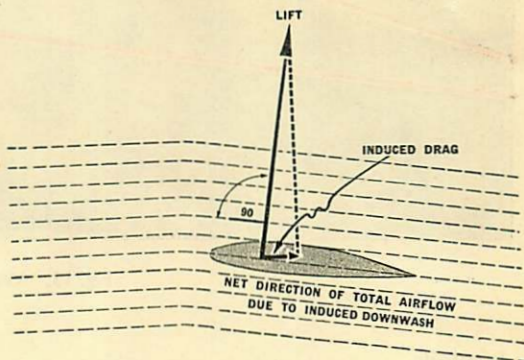


Fig. 12. Induced Drag

Trailing-Edge Vortices

36. The airflow over the top surface tends to flow inwards towards the centre of the low-pressure area, and the airflow under the wing tends to flow outwards away from the high-pressure peak. Therefore when the airflows from the upper and lower surfaces meet at the trailing edge, they do so at an angle to each other and combine in a rotary motion to form vortices along the entire trailing edge. These vortices rotate in the same direction as the main wing-tip vortices.

37. The wing-tip and trailing-edge vortices are greatest at high angles of attack and they disappear at the angle of attack for zero lift. At more negative angles of attack the vortices form again, but the direction of the rotation is reversed. Trailing-edge vortices add to the major effect of the tip vortices and *the total effect of induced drag varies inversely as the square of the indicated air speed.*

38. Methods of reducing the intensity and effects of induced drag are given in Chapter 6, "Wing Plan Forms".

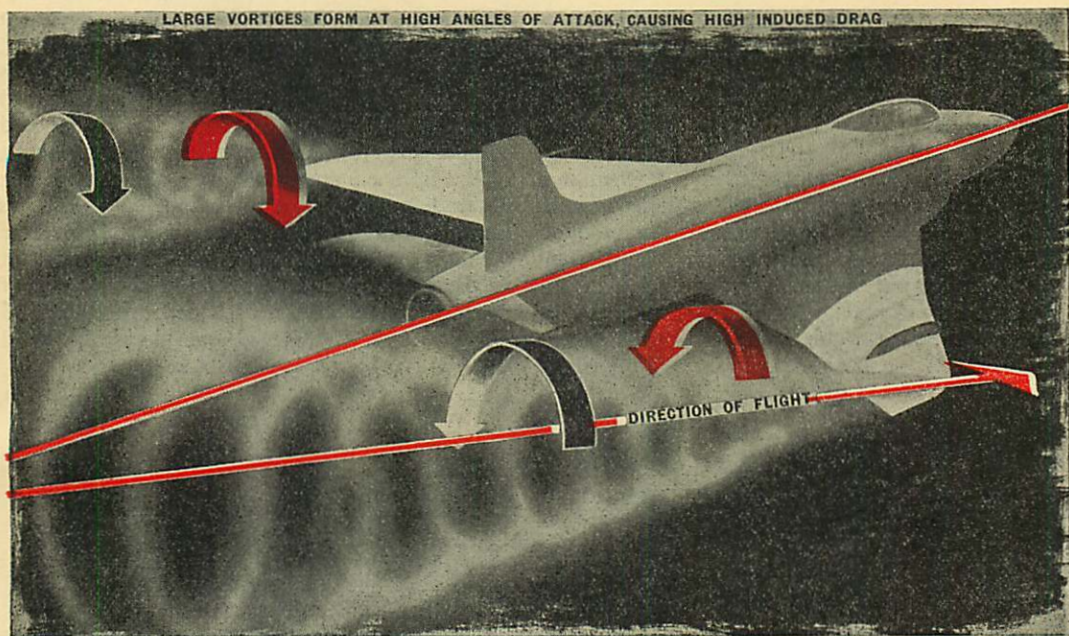


Fig. 13. Wing-Tip Vortices

Aerofoils

39. The performance of an aerofoil is governed by its contour. Generally aerofoils can be divided into three classes:—

- (a) High lift.
- (b) General purpose.
- (c) High speed.

Typical examples of each are illustrated in Fig. 14.

40. **High-Lift Aerofoils.** A typical high-lift section is shown in Fig. 14(a).

(a) There are sections employing a high t/c ratio, a pronounced camber, and a well-rounded leading edge; their maximum thickness is at about 25 per cent. to 30 per cent. of the chord aft of the leading edge.

(b) The greater the camber, *i.e.* the amount of curvature of the mean camber line, the greater the shift of centre of pressure for a given change in the angle of attack. The range of movement of the C.P. is therefore large on a high-lift section. This movement can be greatly decreased by reflexing upwards the trailing edge of the wing, but some lift is lost as a result.

(c) Sections of this type are used mainly on sailplanes and other aircraft where a high C_L is all-important and speed a secondary consideration.

41. **General-Purpose Aerofoils.** A typical general-purpose section is shown in Fig. 14(b).

(a) These are sections employing a lower t/c ratio, less camber, and a sharper leading edge than those of a high-lift type, but their maximum thickness is still at about 25 per cent. to 30 per cent. of the chord aft of the leading edge. The lower t/c ratio, results in less drag and a lower C_L than those of a high-lift aerofoil.

(b) Sections of this type are used on aircraft whose duties require speeds which, although higher than those mentioned in para. 40, are not high enough to subject the aerofoil to the effects of compressibility.

42. **High-Speed Aerofoils.** A typical high-speed section is shown in Fig. 14(c).

(a) These sections employ a very low t/c ratio, no camber, and a sharp leading edge. Their maximum thickness is at about the 50 per cent. chord point.

(b) Most of these sections lie in the 5 per cent. to 10 per cent. t/c ratio band, but even thinner sections have been used on research aircraft. The reason for this is the overriding requirement for low drag; naturally the thinner sections have low maximum-lift coefficients.

(c) High-speed aerofoils are symmetrical about the chord line ; some sections are wedge-shaped whilst others consist of arcs of a circle placed symmetrically about the chord line. The behaviour and aerodynamics of these sections at supersonic speeds are dealt with in detail in Chapter 14, "Transonic and Supersonic Aerodynamics".

43. The performance of all aerofoils is sensitive to small changes in the contour. Increasing or decreasing the camber by as little as 1 per cent. of the chord, or moving the point of maximum camber an inch or so in either direction, will alter all the characteristics. In particular, changes in

the shape of the leading edge have a marked effect on the maximum lift and drag obtained and the behaviour at the stall ; a sharp leading edge stalling more readily than one that is well rounded. For these reasons it is important that the finish of the wing surfaces be carefully preserved if the aircraft is expected to attain its maximum performance. Any dents or scratches in the surface, caused by careless handling, bring about a deterioration in the general performance. These points are of particular importance on high-performance aircraft, when a poor finish, caused through indifference and lack of care, can result in drastic reduction, not only of performance, but also in controllability at high mach numbers.

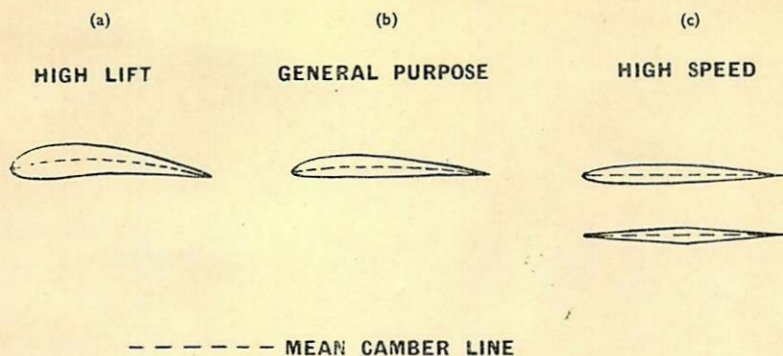


Fig. 14. Representative Aerofoils

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