PART 1 : SECTION 1

CHAPTER 6

WING PLAN FORMS

Introduction

1. The preceding chapters discussed the basic considerations of lift, drag, and stalling, and explained the causes of these phenomena. However, it is now necessary to examine another important aspect of the design of wings, *i.e.* the plan form. The plan form is the geometrical shape of the wing when viewed from above; it largely determines the amount of lift and drag obtainable from a stated wing area and has a pronounced effect on the value of the stalling angle of attack.

2. This chapter is concerned only with the low-speed effects of variations in wing plan forms. The high-speed effects are dealt with in the chapters on high-speed flight.

Aspect Ratio

3. Any plan form can be described briefly, but well enough to give a rough idea of its performance, by its aspect ratio.

4. The aspect ratio (A) of a wing is found by dividing the square of the wing span by the area of the wing, *i.e.*:

$$A = \text{Span}^2/\text{Area}$$

Thus if a wing has an area of 250 square feet and a span of 30 feet, the aspect ratio is 3·6. Another wing with the same span but with an area of 150 square feet would have an aspect ratio of 6. Aspect ratio can also be found by dividing the span by the mean chord of the wing. For example, a span of 50 feet with a mean chord of 5 feet gives aspect ratio of 10. From the foregoing it can be seen that the smaller the area or mean chord in relation to the span the higher is the aspect ratio.

Aspect Ratio and Induced Drag

5. The origin and formation of wing-tip vortices has been explained in Chapter 4, and it was also stated that these vortices were the cause of induced drag. The amount of induced drag under a given set of conditions can be found from the formula:

$$\text{Induced drag} = (C_L{}^2/\pi A)\ \tfrac{1}{2}\rho V^2 S$$

Where $C_L{}^2/\pi A$ = the coefficient of induced drag (C_{DI})

and A = Aspect ratio.

6. Since $\frac{1}{2}\rho V^2 S$ is common to all aerodynamic forces, it is sufficient to consider only the coefficient of induced drag when discussing the subject in general terms. Because the factor A is underneath in the fraction it can be seen that the induced drag is inversely proportional to aspect ratio. The variation is a matter of simple proportion, for if the aspect ratio is doubled then the induced drag will be halved.

7. The dimensions of the wing-tip vortices and therefore the amount of induced drag can be reduced considerably by increasing the aspect ratio. Fig. 1 shows two wings of the same area but with different aspect ratios. The wing with the higher aspect ratio forms smaller wing-tip vortices than the other because a smaller proportion of the total area is involved in the process of spilling air from the lower to the upper surface. Consequently the rate of spilling or circulation around the tips of high aspect ratio wings is less.

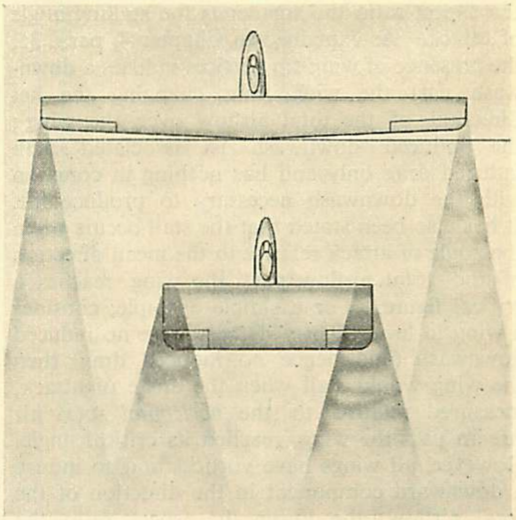

Fig. 1.

Effect of Aspect Ratio on Wing-Tip Vortices

8. The high aspect ratio wing can be said therefore to be more efficient, from the point of view of low induced drag. Since the total drag of a wing is the sum of the profile and induced drags, and the induced drag changes with aspect ratio, the total drag also changes with aspect ratio. The graph of Fig. 2 shows the effect of aspect ratio on the total drag of two wings of different aspect ratios over the working range of angles of attack.

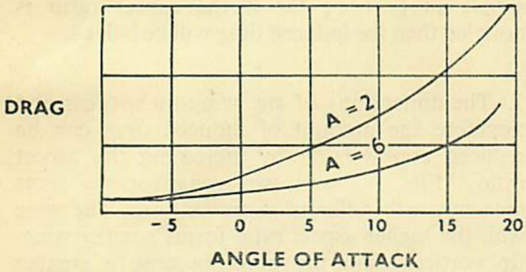

Fig. 2. Effect of Aspect Ratio on Total Drag

Aspect Ratio and Stalling Angle

9. Changing the aspect ratio for a given wing area affects the angle of attack at which a given lift coefficient is obtained.

10. For a given aerofoil section, the higher the aspect ratio the smaller is the stalling angle of attack. As explained in Chapter 4, para. 35, the presence of wing-tip vortices induces a downwash past the wing, thus changing the net direction of the total airflow over the wing; the induced downwash is associated with induced drag only and has nothing in common with the downwash necessary to produce lift. It has also been stated that the stall occurs when the angle of attack relative to the mean direction of the total airflow past the wing reaches a critical figure. For a simple example, consider a wing in level flight: if there were no induced downwash (and hence no induced drag) then the wing would stall when the angle of attack, measured relative to the *horizontal* total air stream past the wing, reached its critical angle. However, all wings have vortices and so induce a downward component in the direction of the total airflow, the lower the aspect ratio the larger the vortices and the greater the induced downwash. Therefore the stall will occur when the angle of attack, measured relative to the mean direction of the total flow past the wing, *which now has a downward component*, reaches the critical angle. In the two cases which have been considered, the stalling angle of the wing with no induced drag is smaller than that of the other by approximately the angular amount of the induced downwash.

11. Thus as the aspect ratio decreases the stalling angle is increased. Wings of aspect ratios of around 20 stall at an angle of attack of about 12°, those of aspect ratios around 8 stall at about 16°, while wings with very low aspect ratios in the region of, say, 2 have stalling angles of about 25°.

Use of High Aspect Ratio

12. High aspect ratio wings are found most often on aircraft having comparatively low cruising I.A.S. At these speeds the angle of attack is approximately that for best lift/drag ratio, about 4°. It has been shown that the total drag is least at this angle of attack but the amount of induced drag may still be fairly large unless the aspect ratio is kept reasonably high. High aspect ratio is most evident on long-range, piston-engined aircraft; on such types the aspect ratio is usually about 10. These figures may be compared to those of smaller short-range aircraft with low cruising speeds; on these aircraft the aspect ratio is usually about 5. An example of very high aspect ratio is to be seen in the wings of high-performance sailplanes where aspect ratios of 25 to 30 are common, low total drag being all-important on these aircraft.

13. The limiting factor in the use of high aspect ratio is the difficulty of providing sufficient strength for the wings without the excessive weight which neutralizes the advantages gained. Broadly it can be said that the lower the cruising speed of the aircraft the higher the aspect ratio that can be usefully employed.

Aspect Ratio and Maximum Lift Coefficient

14. The maximum lift coefficient obtained from a given wing area and aerofoil section is almost unaffected by aspect ratio. However, there is a tendency for the C_L max. to decrease as the aspect ratio is reduced, becoming most noticeable at very low aspect ratios of about 2 to 3. Therefore, stalling speeds, for a given wing loading, are not seriously affected by a reduction in the aspect ratio.

Swept-Back Leading Edges

15. This type of plan form is used on high-speed aircraft and may take the shape of a swept-back wing, or a delta wing with or without a tailplane. The reason for the use of these plan forms is their low drag at the highest speeds. However, the high-speed/low-drag advantages are gained at the cost of a poorer performance at the lower end of the speed scale.

Effect of Sweepback on Lift

16. Any swept-back plan form, delta wing or otherwise, suffers a marked drop in the maximum lift coefficient when compared with an unswept wing of the same area and aspect ratio. Fig. 3 shows typical C_L curves for a straight wing, a simple swept-back wing, and a tailless delta wing of the same low aspect ratio.

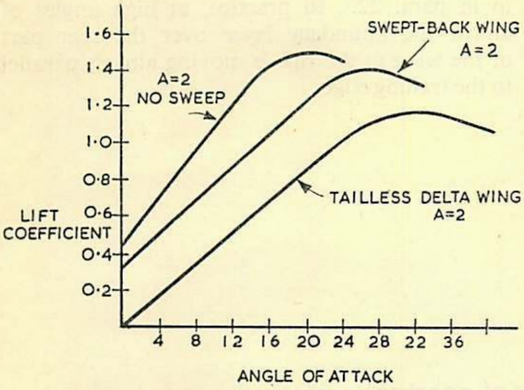

Fig. 3. Effect of Plan Form on C_L max.

17. It can be seen that the stalling angle of the straight wing is about 20° with a C_L max. of about 1·5, while the stalling angles of the swept-back and delta wings are about 24°/1·4 and 30°/1·2 respectively.

18. The stall occurs on all three wings at angles of attack considerably greater than those of wings of medium and high aspect ratios. On all aircraft it is desirable that the landing speed should be close to the lowest possible speed at which the aircraft can fly; to achieve this desirable minimum the wing must be at the angle of attack corresponding to the C_L max.

19. On all wings of very low aspect ratio, and particularly those with a swept-back plan form, the angles of attack giving the highest lift coefficients cannot be used for landing. This is because, as explained later, swept-back plan forms have some undesirable characteristics near the stall, and because the exaggerated nose-up attitude of the aircraft necessitates—among other things—excessively long and heavy undercarriages. The maximum angle at which an aircraft can touch down without recourse to such measures is about 15°, and the angle of attack at touch-down will therefore have to be something of this order. Fig. 3 shows that the C_L corresponding to this angle of attack is lower than the C_L max. for each wing.

20. Compared to the maximum usable lift coefficient available for landing aircraft with unswept wings those of the swept and delta wings are much lower, necessitating higher landing speeds for a given wing loading. It is now apparent that, to obtain a common minimum landing speed at a stated weight, an unswept wing needs a smaller area than either of the swept plan forms. The simple swept wing will need a greater area and so a lower wing loading in order that the reduced C_L can support the weight at the required speed. The tailless delta wing needs still more area and so a still lower wing loading to land at the required speed. Fig. 4 shows typical plan forms for the three types of wing under consideration, with the areas adjusted to give the same stalling speed. The much larger area of the delta wing is evident.

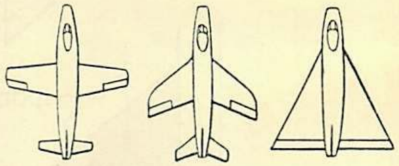

Fig. 4. Typical Plan Forms with Areas Adjusted to Give a Common Stalling Speed

Effect of Sweepback on Stalling

21. There are two main reasons for an accentuated tendency towards tip stalling on swept-back wings :—

(*a*) When a wing is swept back, the effect is to change the distribution of the lift so that the proportion carried by the outer portions of the wing is increased, *i.e.* the local lift coefficients near the wing tips are increased. It has been stated in Chapter 5, para. 39(*a*) that this was a possible cause of the tip stall (*b*) There is a tendency for the boundary layer to change direction and to drift outwards towards the tips and interact with the possibly critical conditions over the tips leading to an early stall in this region. The causes of this outward drift and the reason for the tip stalling are given in paras. 22 to 26.

22. The outward drift of the boundary layer is caused because the air over the wing, and particularly in the boundary layer, is flowing obliquely to the adverse pressure gradient over the rear of the wing. It has been shown that, near the stall, the peak of the low-pressure area over the wing is situated close to the leading edge and that the boundary layer, after having passed this peak, is moving against a rising pressure gradient, which, when added to the effects of friction, leads eventually to separation and a stall.

23. Fig. 5 shows an oblique pressure gradient and its effect. An air stream moving at a given speed and encountering an adverse pressure gradient in which the lines of equal pressure (the isobars) are swept back at an angle to the main airflow. The speed of the flow can be shown by two components, one at right angles and the other parallel to the isobars.

24. The parallel component is not seriously affected by the adverse pressure gradient, moving as it is along a line of constant pressure, but the other component will be subjected to the effects of rising pressure. This means that the component at right angles will be retarded to a greater extent than that parallel to the isobars.

25. Therefore, the direction of flow of the boundary layer is changed until eventually the vertical component is reduced to zero while the parallel component has still the same value. At this stage the boundary layer is flowing outwards parallel to the isobars. This is the outward drift of the boundary layer referred to in para. 22. In practice, at high angles of attack the boundary layer over the rear part of the wing at the tips is moving almost parallel to the trailing edge.

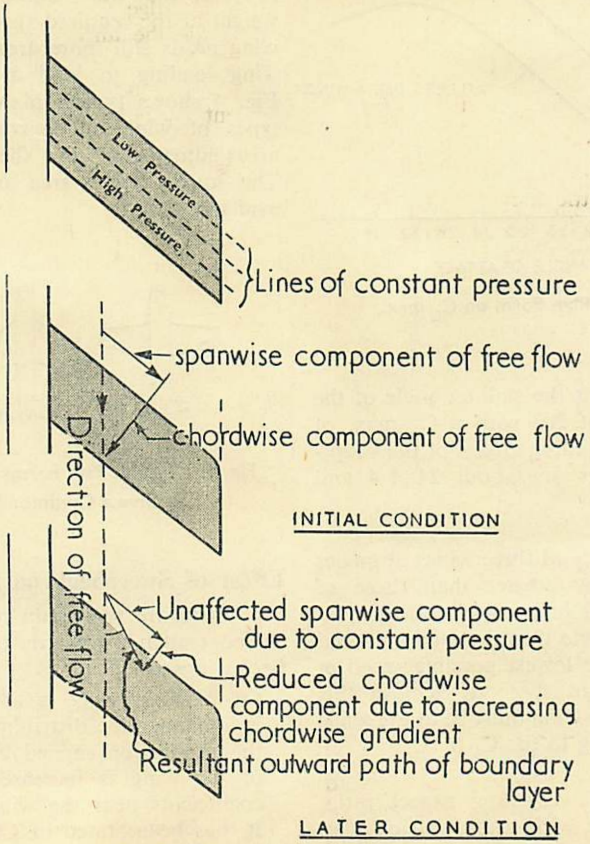

Fig. 5. Effect of Sweepback on Stalling

26. The spanwise drift sets up a tendency towards tip stalling, since it thickens the boundary layer over the outer parts of the wing, thus making for easier separation, bringing with it a sudden reduction in the C_L max. over the wing tips.

27. **Aileron Effectiveness.** The spanwise flow of the boundary layer increases in severity as the angle of attack is increased because of the more pronounced pressure gradient at the higher angles. Since the ailerons of most aircraft are situated at the wing tips, in the region where the adverse effects of the thickened boundary layer are greatest, the effectiveness of the ailerons tends to decrease as the angle of attack is increased. Therefore, comparatively large aileron movements are necessary to manœuvre the aircraft at low speeds to which the aircraft response may be sluggish. A possible solution is to move the ailerons inboard or go to the opposite extreme and use an all-moving wing tip.

28. Tip stalling on wings of swept-back plan forms can be alleviated by the use of most of the devices detailed in Chapter 5, para. 39, but such devices usually conflict with the requirements for high speed. Slats and nose flaps (Chapter 7) are often used to counter tip stalling, as are wing fences (see para. 29). Another method is to reduce the amount of sweepback on the outer sections of the wings, so that the inboard sections are comparatively highly swept whereas the tips have little or even no sweepback. This is known variously as a cranked wing, crescent wing, or compound sweep.

29. **Wing Fences.** These are small chordwise metal strips, a few inches in height, fitted on the upper surfaces of some swept-back wings to improve the stalling characteristics. The fences may extend all the way from the leading edge to the trailing edge or over only a part of the chord. On some wings the fences may even be continued around the leading edge and for a short distance on the lower surface of the wing. Depending on its size and position, the fence relieves the wing-tip stalling tendency either by initiating a local stall inboard of the tip or by restricting the spanwise movement of the boundary layer, or a combination of both.

Tailless Delta Wings

30. On aircraft using this type of wing, the angle of attack is controlled by movement of the trailing edge of the wing; an upward movement produces a downward force on the trailing edge and so increases the angle of attack. When compared to an identical wing which uses a separate tailplane to control the angle of attack, the tailless delta reveals two main differences :—

(*a*) The C_L max. is reduced.

(*b*) The stalling angle is increased.

Reduction in C_L Max.

31. (*a*) In Chapter 4, para. 5, the chord line of the wing was defined as being a straight line joining the leading edge to the trailing edge. If a given wing/aerofoil combination has a hinged trailing edge for use as an elevator, then it can be said that when the trailing edge is in any given angular position the effective aerofoil section of the wing has been changed.

(*b*) When such a wing reaches its stalling angle in level flight, the trailing edge elevator must be raised to impose a downward force on the trailing edge to maintain the wing at the required angle of attack. The raised trailing edge has two effects; it deflects upwards the airflow passing over it and so reduces the downwash, the amount of which is proportional to the lift, and it reduces the extent of both the low-pressure area over the upper surface of the wing and the high-pressure area below, thereby lowering the C_L.

(*c*) The curves of Fig. 6 show that any section with a raised trailing edge must suffer a decreased C_L max. compared to the basic section.

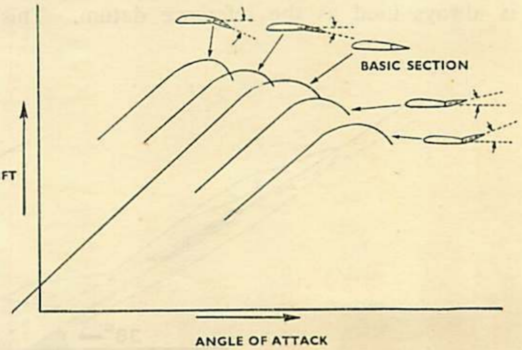

Fig. 6. Effect of Hinged Trailing Edge on C_L max. and Stalling Angle

Increase in Stalling Angle

32. The plan form of the delta wing gives it an inherently low aspect ratio and therefore a high stalling angle and a marked nose-up attitude at the stall in level flight. If a certain delta wing is used without a tailplane, *i.e.* the trailing edge is used as an elevator, then the stalling angle is higher than when the same wing is used in conjunction with a tailplane.

33. *All else being equal* (plan form, aspect ratio, area, etc.), changes in the amount of camber (by altering the angular setting of the trailing edge elevator) do not affect the stalling angle appreciably. That is, the angle between the chord line (*drawn through the leading and trailing edges*) and the direction of the airflow remains constant when at maximum C_L irrespective of the setting of the hinged trailing edge. Fig. 7 illustrates this point and it can be seen that for both the "tailed" and "tailless" aircraft the stalling angle is the same when measured on the foregoing principles.

34. However, it is normal practice and convention to measure the stalling angle with reference to the chord line obtained when the moveable trailing edge is in the neutral position and not to assume a new chord line with each change in trailing edge movement. When the stalling angle is measured with reference to the conventional fixed chord line it can be seen from Fig. 7 that the angle is greater. Fig. 7 also shows that because the wing proper is set at a greater angle at the stall when a trailing edge elevator is used, the fuselage attitude is more nose-up, giving a more exaggerated attitude at the stall in level flight.

35. Since it is easier to refer to angle of attack against a fixed chord line, the basic chord line is always used as the reference datum. This convention is the reason for the apparently greater stalling angles of tailless delta wings; it is perhaps a more realistic method, as the pilot is invariably aware of the increased *attitude* of his aircraft relative to the horizontal, but is not always aware of increases in the angle of attack.

The C_L Curve

36. Reference to Fig. 3 shows that the peak of the curve for the lift coefficient is very flat and shows little variation of C_L over a comparatively wide range of angles. This very mild stalling behaviour enables the delta wing to be flown at an angle of attack considerably higher than that of the C_L max., possibly with no ill effects other than the very marked increase in the drag (para. 38). The flat peak denotes a gradual stall with a consequent gradual loss of lift as the stalling angle is exceeded.

Pitch-Up

37. This undesirable self-stalling characteristic occurs to a varying degree on most aircraft which use sweepback. It consists of an abrupt upward pitching of the nose at high angles of attack, after the initial stall warning buffet, if any, has occurred but before the full stall has developed, and is caused by the stalling of the wing tips. When this occurs the lift over the highly loaded outboard portions is lost, resulting in an inward movement of the centre of lift along a line about 25 per cent. from the leading edge. Since the wing is swept back this movement automatically takes the centre of pressure of the complete wing forward resulting in a concentration of lift over the inboard parts of the wing. This causes an increase in the downwash over the tailplane and thus an additional nose-up force is applied. Pitch-up can be cured either by eliminating the wing-tip stall or by placing

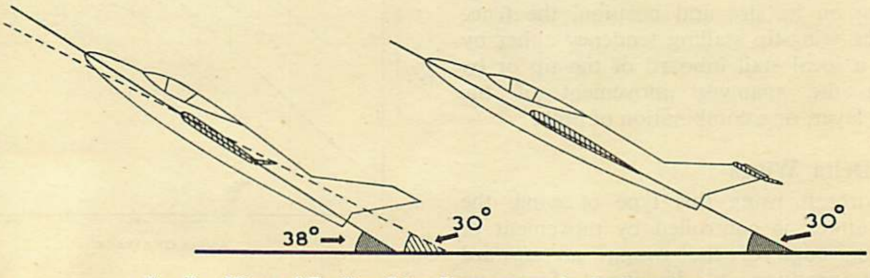

Fig. 7. Effect of Trailing Edge Elevator on the Stalling Angle

the tailplane in a region which is not subjected to high downwash. A tailplane located below the wing chord line will achieve this. Pitch-up can also occur in a violent form while manœuvring at high speeds; this aspect is dealt with in Chapter 12, "Manœuvres". From the pilot's point of view, pitch-up can be recognized when the pull force on the control column which was being applied to stall the aircraft has to be changed suddenly to a push force to prevent the nose from rising further. Pitch-up in a stall in level flight is usually not violent. The initial nose-up pitch is often followed by a nose-down pitch when the stall spreads over the whole wing.

Effect of Sweepback on Drag

38. Fig. 8A is a graph for a typical swept-back wing, plotting lift against drag over the range of angles of attack. The left-hand point represents the angle of attack for best L/D ratio. The graph shows clearly the large increase of drag that occurs at high angles of attack (an effect of induced drag) and that the rate of increase of drag becomes very high at about the stalling angle.

39. The practical significance of this high drag is shown in Fig. 8B which plots air speed against rate of climb or descent during a landing approach at a low engine power. At the correct approach speed the L/D ratio results in a moderate rate of sink on the approach; if the pilot then raises the nose, to decrease speed (without increasing power), the lift is increased but at the same time an appreciable drag increase occurs and the rate of sink may be almost doubled for a comparatively small loss in speed. At still lower speeds (higher C_L) the drag rise is so large and the L/D ratio falls off so quickly that the use of even full power may be barely enough to prevent the aircraft sinking rapidly—this is known as a *super-stalled* condition.

40. For this reason the pilot should always anticipate any reduction in speed during an approach with an increase of engine power; this increase may have to be quite appreciable.

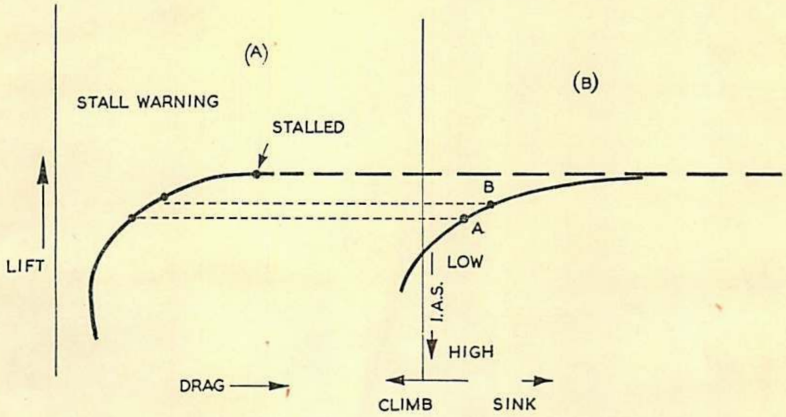

Fig. 8. Effect of Sweepback on Drag