PART 1 : SECTION 1

CHAPTER 5

STALLING

Introduction

1. In the previous chapter an imaginary aerofoil was examined and its performance ascertained by placing it in an air stream moving at a fixed speed, and then measuring the resulting forces, throughout the working range of angles of attack.

2. In steady flight any one wing always stalls at the same angle of attack ; but the speed at which it stalls depends on a number of factors. It is important that the pilot be well acquainted with the causes and effects of stalling, since this gives him a better understanding of the nature of the stall and enables him to handle his aircraft more confidently at the low speeds with which every flight begins and ends, *i.e.* when the margin of speed above the stall is small. Since the stalling speed of a typical high-performance aircraft may vary, for example, between 100 knots I.A.S. and 130 knots I.A.S., depending on the weight, this margin of speed must be adjusted to fit the circumstances. The pilot who appreciates the effect of variables on the stalling speed of the aircraft is able to fly to closer limits with greater confidence and safety than one who does not.

3. **Lift Formula and the Stall.** The lift of a wing is calculated from the formula :

Lift = $C_L \frac{1}{2}\rho V^2 S$, where :—

C_L = The lift coefficient at the required angle of attack.

ρ = The density of the air at the required altitude in slugs per cubic foot.

V^2 = The square of the speed in feet per second.

S = The wing area in square feet.

4. In level flight the weight of the aircraft is balanced by the lift, and from the lift formula it can be seen that the lift decreases whenever any of the terms which make up the formula are decreased, and vice versa. In level flight, if the engine is throttled back, the drag immediately causes a reduction in speed ; and therefore the lift follows suit. To keep the lift constant, and so maintain level flight in spite of the reduced speed, some other term of the lift formula must be increased. Density (ρ) and wing area (S) are constant for all practical purposes ; therefore the only remaining factor which is readily variable is the lift coefficient (C_L).

5. As has been shown, the C_L can be made larger by increasing the angle of attack, and by so doing the lift can be restored to its original value so that level flight is maintained at the reduced speed. Any further reduction in speed necessitates a further increase in angle of attack, *each succeeding lower I.A.S. corresponding to each succeeding higher angle of attack*. Eventually, at a certain I.A.S., the wing reaches its stalling angle, beyond which point any further increase in angle of attack, in an attempt to maintain the lift, will precipitate a stall.

6. Since there is no instrument fitted to measure the angle of attack, the only indication of the approach of the stall is the air speed indicator, the speed at which the stall occurs being known as the *stalling speed.*

Effect of Weight (Wing Loading) on the Stall

7. It has been stated that, in level flight, each I.A.S., including the stalling speed, corresponds to a particular angle of attack ; however this statement is true *only at one weight, or wing loading*. Consider a wing which is producing sufficient lift to support a stated weight and is flying just below the stalling angle. If additional weight is placed on the wing, the new weight is greater than the lift and level flight is no longer possible under the same conditions.

8. To maintain level flight more lift must be produced and this can be done by increasing either the angle of attack or the speed. Because the angle of attack, in the example, is almost at the stall, this cannot be increased without losing lift ; it is therefore necessary to increase the speed to some higher figure until the lift again equals the weight. Therefore, although the angle of attack is still unchanged at a figure on the verge of the stall, the corresponding speed, *i.e.* the stalling speed, is higher. This new relationship holds good at all combinations of angle of attack and air speed. In other words, at the greater weight or wing loading the speed corresponding to a given angle of attack is higher than the speed necessary at a lower wing loading.

9. To sum up, there is a minimum speed (the stalling speed) at which a wing can sustain a stated wing loading in level flight. The greater the wing loading the greater the stalling speed, and vice versa.

10. Fig. 1 shows graphically the marked effect of weight on the stalling speed of a fighter aircraft. The shape of the graph varies between different aircraft, and detailed information on the stalling speeds at various weights is given in Pilots' Notes for each type of aircraft.

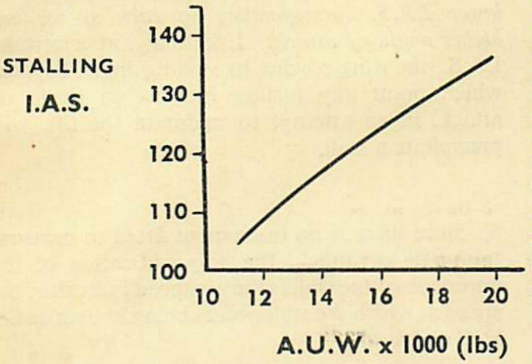

Fig. 1. Effect of Weight on the Stalling Speed

11. If the stalling speed, in level flight, is known for one weight, then the approximate stalling speed at any other weight can be calculated from the formula :

$$V_2 = V_1\sqrt{\frac{W_2}{W_1}}$$

where V_2 = new stalling speed,
V_1 = original stalling speed,
W_2 = new weight,
W_1 = original weight.

Boundary Layer and the Stall

12. The boundary layer, as explained in Chapter 3, is the thin film of air in immediate contact with the surface over which the air is flowing. The behaviour and flow characteristics of the boundary layer are of great importance in the understanding of even basic aerodynamics. Many of the problems of the designer centre around the effects of the boundary layer on the main airflow around the aircraft and into the air intakes of jet engines.

13. The fundamental cause of the "breakaway" of the airflow over a wing at high angles of attack is due to the action of the boundary layer, and the following paragraphs deal in some detail with the behaviour of the boundary layer under different conditions of flight.

14. If a wing is placed in a low-speed airflow, the air particles of which are visible, then the pattern of the airflow around the wing can be studied. Such a study reveals that the boundary layer stands out clearly from the main flow and is found to take the form shown in Fig. 2.

15. **Rotational and Irrotational Flow.** On examining the flow in the boundary layer closely, it will be seen that it differs from the free air stream in that the particles of air are rotating as they move rearwards, those on the upper surface in a clockwise direction and those below anti-clockwise—in exactly the same way as ball bearings would do if rolled along the surface. The flow in the boundary layer is therefore termed *rotational flow* while that in the free air stream is termed *irrotational.* Rotational flow, and hence drag, is caused whenever any friction exists between the air and the surface it is flowing over. In the free air stream, where there are no friction effects, the air particles are in a state of steady irrotational flow.

16. **Stagnation and Separation Points.** The stagnation point, as shown in Fig. 2, is that point at which the air is brought to rest by the leading edge and the point from which the boundary layer originates. The separation points are the points on the wing at which the boundary layers break away from the surface. The wake consists of the unsteady rotational flow, resulting from the separation of the boundary layers from the wing, which tends to be dragged behind the trailing edge. For a chord of seven feet the wake is about four to five inches in depth during flight at small angles of attack.

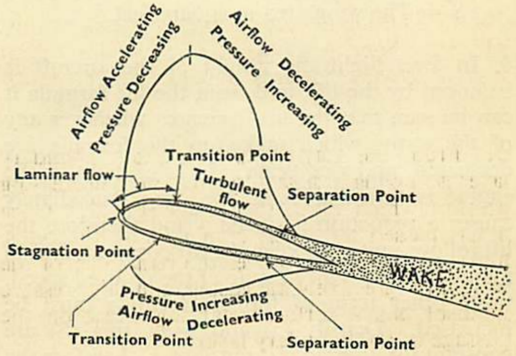

Fig. 2. The Boundary Layer

17. **Unsteady Flow.** The air particles in the free air stream are in a state of steady flow parallel to the streamlines. The air particles in the wake, however, are in unsteady flow and move rapidly and unpredictably around within the confines of the wake. Further, the speed in the wake is much lower than that of the free air stream. These are natural effects of the frictional forces between the wing surface and the boundary layer.

18. The boundary layer is very thin over most of the wing and has a negligible effect on the pressure distribution, except near the trailing edge where separation occurs. The considerable thickening which takes place after separation has occurred, is sufficient to cause a marked reduction in the lift obtained from this area of the wing. One of the features of a good aerofoil is that the separation point is close to the trailing edge and, therefore, the losses incurred through the presence of a wake forming over the trailing edge are kept to a minimum.

Airflow in the Boundary Layer

19. From the stagnation point the boundary layer has an initial motion called laminar flow, similar to the sliding of successive very thin layers past each other ; the lowest layer being stationary and that furthest from the surface moving at the speed of the free flow. Through this very thin layer the velocity gradient rises from zero up to that of the main flow. Therefore a considerable shear force exists through the boundary layer. As the layer moves aft over the wing more layers of air take on the sliding motion and the thickness of the boundary layer increases as frictional and other effects become more pronounced. Laminar flow is very sensitive and requires only the smallest inducement to give way to its turbulent counterpart.

20. In addition to the frictional effects against which the boundary layer has to make its way, it is also moving towards a region of increasing pressure.

21. From the stagnation point, the boundary layer is moving at first into a region of decreasing pressure which assists its passage (Fig. 2). Once it has passed the point of maximum thickness, however, the pressure over the remainder of the wing is progressively increasing, and this pressure gradient has a further retarding effect on the passage of the boundary layer.

22. The effect of the forces opposing the movement of the boundary layer is to cause the laminar flow to become unstable, and to break down suddenly into turbulence. At the same time, the thickness of the layer increases.

23. The point at which the changeover from laminar to turbulent flow occurs is called *the transition point* and on a smooth wing it is located roughly at about the point of maximum thickness. A badly finished wing with a roughened or scratched surface will cause the transition point to move forward.

24. As the turbulent boundary layer moves further downstream further progressive thickening, due to the friction and pressure gradient, takes place. This process continues until the total effect of the friction and pressure gradient factors brings the entire boundary layer to rest, at which point it separates from the wing and forms a turbulent wake ; aft of the point at which the wake begins, the pressure distribution is weakened and a loss of lift occurs.

Pressure Gradients and the Boundary Layer

25. Chapter 4 described how the pressure distribution changes with increase of angle of attack. It can be seen that close to the leading edge there is a marked peak of low pressure immediately behind which there is a rapidly increasing pressure gradient.

26. If the adverse gradient is sufficiently strong, the entire boundary layer is brought to rest. When this happens, the flow separates from the upper surface and the breakaway associated with the stall occurs. In the region of the breakaway the airflow is rotational and turbulent.

27. The stall, then, occurs when the increasing pressure gradient which exists on the top surface of all aerofoils becomes too great for the boundary layer to force its way through. The result of this is that the flow no longer follows the wing contour and breaks away at a point just behind the leading edge with an accompanying large loss of lift.

28. **Separation.** It has been found that a laminar boundary layer separates more readily in the presence of an adverse pressure gradient than a turbulent boundary layer. This is because the momentum of the main flow is not readily transferred to the lower layers of a laminar layer ; therefore, in the absence of this assistance, it is brought to rest sooner by the effect of friction and the pressure gradient, and separates. A

turbulent boundary layer, on the other hand, obtains some energy from the main flow, so enabling the layer to force its way against the decelerating effects of friction and increasing pressure ; energy is taken from the main flow by air in the upper portion of the rotational boundary layer, the rotation then carrying the accelerated air to the lower parts of the boundary layer, thus raising the energy of the complete layer.

29. From the foregoing it will be seen that in order to prevent separation and obtain better stalling characteristics a turbulent boundary layer is desirable. However, the turbulent boundary layer conflicts with the requirements for low drag which demand a laminar boundary layer. One of the problems of the designer is to decide which type of boundary layer will best suit the purpose of a particular aircraft.

Laminar Flow Aerofoils

30. Chapter 4 described the features of the principal classes of aerofoils. It stated that on high-speed (or low-drag) aerofoils, the point of maximum thickness is situated at about the 50 per cent. chord position. One reason for this can now be understood. While the airflow is accelerating towards the point of maximum thickness the pressure gradient is decreasing, thus setting up more favourable conditions for maintaining a laminar boundary layer. In other words, these aerofoils have the effect of moving the transition point of the boundary layer further aft.

31. A more rearward transition point means that a great area of the wing is covered by a laminar flow and therefore the skin friction drag is less.

32. An important requirement of these aerofoils, if they are to attain the maximum amount of laminar flow and give least drag, is that their surfaces must be as smooth and as highly polished as possible. Any irregularity on the surface, the smallest nick or scratch, is sufficient to cause a breakdown at that point in the always sensitive laminar flow. The result of such a breakdown is the fanwise growth of a turbulent boundary layer from the small local transition point. The carefully finished surfaces of high-speed aircraft are intended primarily for the cultivation of laminar flow and much depends, from the point of view of performance, on the maintenance of this finish.

33. Assuming that the boundary layer reaches the point of maximum thickness while in laminar form, the transition point lies almost immediately after this, as soon as the pressure gradient begins to rise.

34. Because there is only a relatively short distance to travel before the trailing edge is reached, and because the adverse pressure gradient is not as steep as that of the low-speed aerofoil, the energy of the turbulent layer is sufficient to carry it almost to the trailing edge before separation occurs. The result of this is a thinner wake and therefore a reduction in form drag ; since the skin friction drag has also been decreased the sum effect, the profile drag, is also less.

35. These advantages are obtained at the expense of a reduced maximum lift coefficient and hence, for a given wing loading, the stalling speed is higher on an aircraft using this type of aerofoil.

Wing-Tip Stalling

36. When a stall occurs in level flight, the resulting fall in lift usually causes the nose of the aircraft to drop. After the nose has dropped the speed increases as the aircraft automatically dives and regains flying speed. This is a safe and desirable characteristic.

37. On many aircraft, however, the stall does not occur simultaneously over the entire wing, one section, usually the tip, stalling earlier than another. This unequal stalling causes a local reduction in the lift coefficient over the affected section. The remainder of the wing being unaffected, the result is a tendency to roll towards the stalled wing. The extent and suddenness of the stall determines the rate at which the rolling motion takes place.

Autorotation

38. The fact that one wing may drop at the stall, either intentionally or otherwise, is the basic cause of spinning. This may be seen by reference to the graphs showing variation of C_L and C_D with the angle of attack (Fig. 3). Suppose that a wing is just at the stalling angle and therefore at the peak of the C_L curve ; if the aircraft now rolls for some reason, the angle of attack on the down-going wing, particularly at the tip, is increased to some figure greater than the stalling angle, while that on the up-going wing is reduced. As a result of the decrease in lift which accompanies the stall, the total lift on the down-going wing is less than that on the rising wing and so a destabilizing rolling motion is set up. The C_D

curve shows that, after the stall, there is a marked increase in drag, and the drag on the down-going wing is therefore higher than that on the other. This results in a moment which yaws the nose towards the down-going wing, *i.e.* a tendency to hold back the wing which is dropping, and so cause it to lose still more speed and lift. If this cycle continues the result is a stalled wing with the nose of the aircraft rotating automatically towards the lower wing. This is known as autorotation. Chapter 8 deals with further aspects of autorotation.

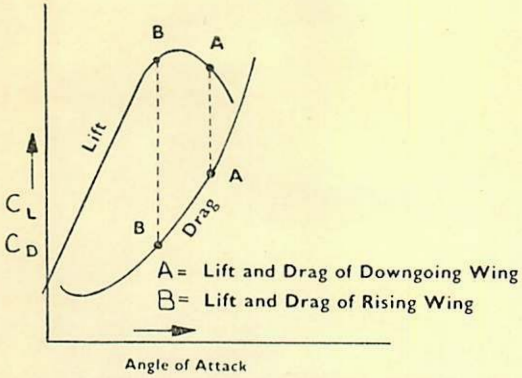

Fig. 3. Autorotation

Methods of Preventing Tip Stalling

39. The undesirable tendency towards wing-dropping, which occurs on many aircraft, can be reduced by incorporating some or all of the following measures in the design of the aircraft:—

(*a*) The avoidance of high local lift coefficients near the wing tips, the unequal collapse of which would cause a strong rolling motion; highly tapered wings have high-lift coefficients over the wing tips.

(*b*) Reducing the angle of incidence over the outer portion of the wing; this is known as *wash-out*. The use of wash-out ensures that the inner portions of the wing reach the stalling angle of attack before the wing tips.

(*c*) Using an aerofoil section at the wing tip that stalls gradually. This is shown by the C_L curve for the section having a flat, well-rounded peak; any C_L curve which has a sharp peak, with a large drop immediately after the stall is indicative of bad stalling characteristics; cambered sections are generally better than symmetrical sections. This change of section towards the tip can be seen on a number of aircraft, the tip sometimes having a concave under-surface, while the inner portions have a convex under-surface.

(*d*) The use of devices, on the outer part of the wing, which increase the stalling angle (see Chapter 7).

(*e*) The fitting of spoilers on the inboard leading edge of the wing to induce a stall over these portions before the tip itself stalls. The spoilers are metal strips attached to the leading edge having a chord of about one inch and a length of about two feet. These have the effect of making a sharper leading edge which stalls more readily than a well-rounded one.