

LIFT AUGMENTATION

Introduction

1. The problem of augmenting the maximum lift coefficient to decrease the speed at the lower end of the speed range has always been given as much attention as the search for higher speeds. This chapter explains the principal methods that are used to increase the maximum lift coefficient.

2. The use of high-speed aerofoil sections helps the designer to achieve higher speeds by reducing the drag, but this gain is paid for by the low maximum lift coefficients of these aerofoils. As most aircraft using these aerofoils also have high wing loadings, the stalling speeds are proportionately higher. While high landing speeds, in themselves, are not a disadvantage, the length of runway required to operate the aircraft sets a limit on the usefulness and operational flexibility of the aircraft.

Principal Methods in Use

3. The chief devices used to augment the C_L max. are :—

- (a) Slats.
- (b) Flaps.
- (c) Boundary-layer control.

Slats

4. When a small auxiliary aerofoil slat of highly cambered section is fixed to the leading edge of a wing along the complete span and adjusted so that a suitable slot is formed between the two, the C_L max. is increased by as much as 70 per cent. and more. At the same time, the stalling angle is increased by some 10° . The graph of Fig. 1 shows the comparative figures for a slatted and unslatted wing of the same basic dimensions.

5. The effect of the slat is to prolong the lift curve by delaying the stall until a higher angle of attack. When operating at high angles of attack the slat itself is generating a high lift coefficient because of its marked camber. The action of the slat is to flatten the marked peak of the low-pressure envelope at high angles of attack and to change it to one with a more gradual pressure gradient. The flattening of the lift distribution envelope means that the boundary layer does not undergo the sudden thickening that occurred

through having to negotiate the very steep gradient that existed immediately behind the former suction peak and so retains much of its energy, thus enabling it to penetrate almost the full chord of the wing before separating. Fig. 2 shows the alleviating effect of the slat on the low-pressure peak and that, although flatter, the area of the low-pressure region, which is proportional to its strength, is unchanged or even increased. The passage of the boundary layer over the wing is assisted by the fact that the air flowing through the slot is speeded up by the venturi effect, thus adding to the kinetic energy of the boundary layer and so helping it to penetrate further against the adverse gradient.

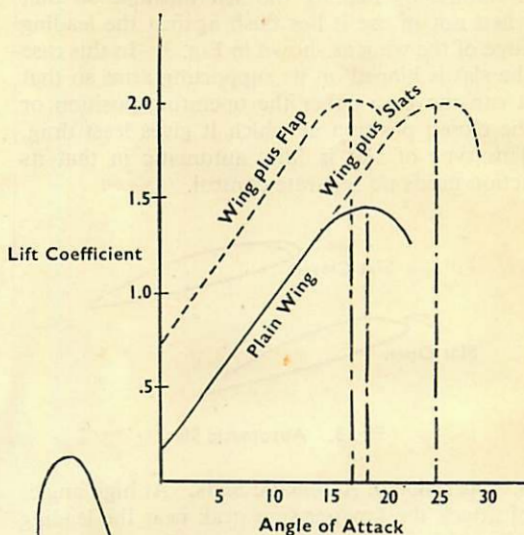


Fig. 1. Effect of the Slat on Lift

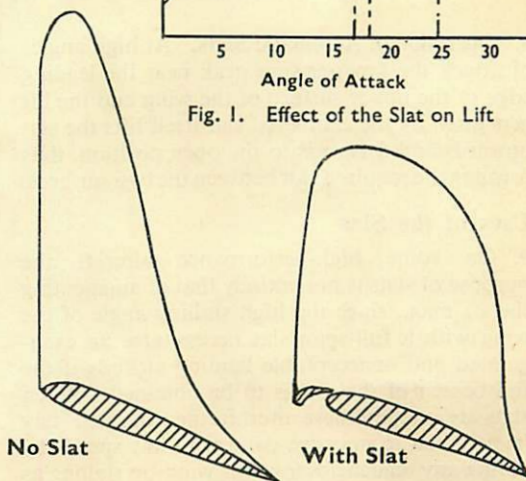


Fig. 2. Effect of the Slat on the Pressure Distribution

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

Automatic Slats

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



Fig. 3. Automatic Slat

8. **Operation of Automatic Slats.** At high angles of attack the low-pressure peak near the leading edge of the upper surface of the wing and the lift generated by the cambered slat itself lifts the slat upwards and forwards to the open position, thus forming the required slot between the two surfaces.

Uses of the Slat

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

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

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

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

13. **Stalling with Slats.** The effect of the slat at the highest angles of attack is to boost the extent of the low-pressure area over the wing. At angles of attack of about 25° the low-pressure envelope has been considerably enlarged and a proportionately larger amount of lift is being developed. When the wing reaches a certain angle the slat can no longer postpone events and the stall occurs. When the powerful low-pressure envelope collapses the sudden loss of lift may result in equally sudden changes in the attitude of the

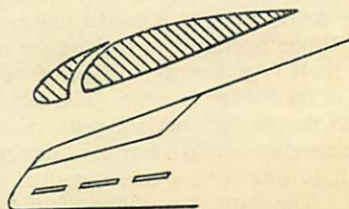


Fig. 4. Built-In Slot

aircraft. This applies particularly if one wing stalls before the other; in this case a strong rolling moment or wing dropping motion would be set up.

Flaps

14. An obvious method of increasing the lift is by variable-area wings, but, while aerodynamically sound, this idea is structurally difficult and the complications outweigh the advantages. The alternative to variation in wing area is the variation of lift coefficient by changing the amount of camber of the aerofoil section in flight. It has been stated that high-lift aerofoil

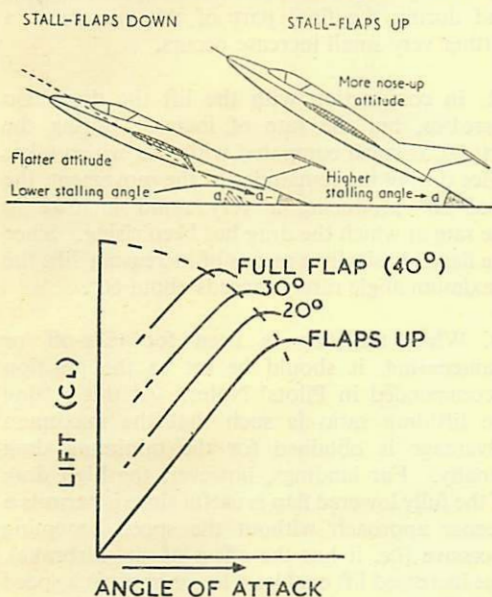


Fig. 5. Effect of Flap on Stalling Angle, and Level Flight Stalling Attitude

sections possess a curved mean camber line (the line equidistant from the upper and lower surfaces). The greater the curvature the better the lifting capabilities by virtue of the increased "circulation" of the air over the upper surface. Therefore, if an aerofoil that has a straight or nearly straight mean camber line has all or a portion of the leading and trailing edges hinged so that they can be moved down, the effect is to produce a more highly cambered aerofoil with the result that, under a given set of conditions, the lift coefficient is increased.

Action of the Flap

15. Increased camber can be obtained by turning down either the leading or the trailing edge or both. In most aircraft the

trailing edge alone is used. The effect of this increased camber increases the lift, but since the change in camber is abrupt the total increase is not as much as would be obtained from a properly curved mean camber line. Fig. 1 shows the effect of flaps and slats on the C_L max. and stalling angle.

16. **Types of Flaps.** The trailing edge flap has many variations, all of which serve to increase the C_L max. Some, however, are more efficient than others as is shown in Fig. 6. The more efficient flaps are usually more complex mechanically and their use is resorted to only when the lowest possible stalling speed is essential. Fig. 6 also shows the effect of combinations of slats and flaps, and of forming a slot immediately in front of the flap. In the latter case the action of the slot is again to set up a favourable pressure gradient and so maintain a suitable boundary layer for a greater distance over the sharply deflected surface of the flap. The Fowler flap is of the area-increasing type and so, besides augmenting the C_L by increasing the camber, it

	Typical Stalling Angle of Attack	Typical Increase in C_L MAX
PLAIN AEROFOIL	17°	
SLOTTED FLAP	14°	53%
SLAT	26°	25%
SLOTTED FLAP PLUS SLAT	20°	75%
SPLIT FLAP	15°	70%
FOWLER FLAP	17°	90%

Fig. 6. Types of Flaps and their Effect

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increases the wing area and in so doing reduces the wing loading thus lowering the stalling speed still further. The Fairey flap (not illustrated), or what is sometimes known as an auxiliary aerofoil flap, is supported on brackets and can be set to three different positions. At the first position it is used for manoeuvring (this aspect is dealt with in Chapter 12). The second position is used for take-off and the third position for landing. Notice that the flap takes the form of a separate aerofoil surface, and is thus of the area-increasing type. The table showing the angles of attack at which maximum lift coefficient is obtained indicates that the flap gives its increased lift coefficient without the attendant exaggerated angles made necessary with slats. The reason for this reduced stalling angle is given in the next paragraph.

Effect of Flap on the Stalling Angle

17. When the trailing-edge flap is lowered the angle of attack for level flight under the prevailing conditions is *reduced*. For each increasing flap angle there is a fixed and lower stalling angle of attack as shown in Chapter 6, Fig. 6. The lower stalling angle is caused through the change in the aerofoil section when the flap is lowered. Paras. 32 to 35 of Chapter 6 describe how the use of a trailing edge elevator on a delta wing *increases* the stalling angle and aircraft attitude at the stall. The same approach can be used to account for the effect of flap on the stalling angle.

18. The trailing edge flap is directly comparable to the trailing edge elevator insofar as the effect on stalling angle is concerned. The *raised* trailing edge elevator at the stall *increases* the stalling angle of attack and the aircraft attitude in level flight but the *lowered* trailing edge flap *reduces* the stalling angle and the aircraft attitude at the level-flight stall. Fig. 5 illustrates how the lowered flap affects the angle of attack and the aircraft attitude. Pilots should take care not to confuse attitude with angle of attack, for, as explained in Chapter 12, the attitude of the aircraft has no fixed relationship with the angle of attack while manoeuvring.

Effect of Flap on the Lift/Drag Ratio

19. Lowering the flaps produces an increase in the lift coefficient at a given speed but at the same time the greater camber also causes an increase in the total drag.

20. It can be stated that when the flaps are lowered to a given angle the lift/drag ratio is

always reduced. The best lift/drag ratio with the flaps lowered is obtained with the flap at some angle between 15° and 35°, the exact angle depending principally on the aerofoil section used and the type of flap employed and its area. The Pilots' Notes for each aircraft specify the optimum flap angle to give the best lift/drag ratio with the flap down.

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

22. In conjunction with the lift the drag also increases, but the rate of increase during the first 30° is small compared with that which takes place during the remainder of the movement, the final 30° producing a very rapid increase in the rate at which the drag has been rising. Since the flap is basically a means of increasing lift, the maximum angle rarely exceeds about 60°.

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

Use of Flap for Take-Off

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

25. When the take-off is made at or near the maximum permissible weight, the flaps should



Fig. 7. Leading Edge Flaps

Curved fairings moving with the flaps cover the gap that would otherwise exist between the flaps and the wings.

invariably be set to the recommended take-off angle so that the maximum lifting effort can be obtained from the wing.

26. **Raising the Flaps in Flight.** Shortly after the take-off, while the aircraft is accelerating and climbing slightly, the action of raising the flaps causes an immediate reduction in the lift coefficient and the aircraft loses height or sinks unless this is countered by an increase in the angle of attack. If the angle of attack is not increased, *i.e.* if the pilot makes no correcting movement with the control column, the reduced lift coefficient results in a loss of lift which causes the aircraft to lose height until it has accelerated to a higher airspeed that counterbalances the effect of the reduced C_L . When the flaps are raised and the effect countered by an increased angle of attack, the *attitude* of the aircraft becomes noticeably more nose-up as the angle of attack is increased. The more efficient the flaps the greater is the associated drop in lift coefficient and the larger the subsequent corrections that are needed to prevent loss of height.

27. On some aircraft it is recommended that the flaps should be raised in stages so as to reduce the C_L gradually and so avoid any marked and possibly exaggerated corrections. This applies sometimes when aircraft are heavily loaded, particularly in the larger types of aircraft.

Leading Edge Flaps

28. Fig. 7 shows a typical leading edge flap. The effect is, as with other flaps, to increase the C_L and lower the stalling speed. However, the fact that it is the leading edge and not the trailing edge that is drooped results in an *increase* in the

stalling angle, and the level-flight stalling attitude. The difference is explained as before (Chapter 6, para. 32, and para. 17 of this chapter), by the fact that although the stalling angle measured with respect to the chord line joining the leading and trailing edges of the changed section is not affected, the stalling angle is increased when measured, as is conventional, with respect to the chord line of the wing with the flap fully raised. Fig. 8 illustrates this point. Leading edge flaps are invariably used in conjunction with trailing edge flaps. The operation of the leading edge flap can be controlled directly from the cockpit or it can be linked, for example, with the airspeed measuring system so that the flaps droop when the speed falls below a certain minimum and vice versa.

29. The effect of leading-edge flaps is similar to that of slats except that the stalling angle is not increased as much. The amount of increase in the C_L max. is about the same in both cases. The leading edge flap is sometimes referred to as a nose flap.

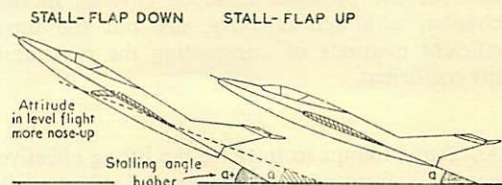


Fig. 8. Effect of Leading Edge Flap on Stalling Angle

Effect of Flaps on Swept-Back Wings

30. When the flap is mounted on a trailing edge that is swept back, the lowered flap is presented

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to the airflow in a swept-back attitude. Viewed from the front, the greater the sweepback the smaller is the frontal area of the flaps exposed to the effects of the oncoming airflow. Therefore, as the angle of sweep is increased, the frontal area becomes smaller and so the effectiveness of the flaps is reduced. Whereas the difference between the flaps-up and flaps-down stalling speeds on unswept aircraft is of the order of 10 to 15 knots, the corresponding speeds on swept wings are from 5 to 10 knots and it is not often that the higher figure is realized.

Effect of Flaps on Wing-Tip Stalling

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

Boundary-Layer Control

32. Thin aerofoils, swept-back plan forms and high wing loadings are all necessary adjuncts to the high-speed aircraft: unfortunately all these features are incompatible with the low-speed requirements for landing and take-off. Hence there is a need for a method of increasing the lifting effectiveness or C_L max. of the wings of high-performance aircraft. The use of either or both of the previous methods covered in this chapter, although effective, are not the most efficient methods of augmenting the maximum lift coefficient.

33. Any attempt to increase the lifting effectiveness of a given wing, directly and fundamentally concerns the boundary layer. If the boundary layer can be made to remain laminar and unseparated as it moves over the wing, then not only is the lift coefficient increased but both skin friction drag and form drag are reduced. The last two effects, however, are incidental to the purpose of these paragraphs.

34. Boundary-layer control is the name given to the method of preventing boundary-layer separation by the use of a separate power source. There are two methods by which the application of power can be used to improve the flow of the boundary layer and thus augment the lift coefficient:—

(a) The use of strong suction through suitably positioned slots or a special porous area in the wing.

(b) The use of air that is blown tangentially to the surface of the wing through suitably positioned slots.

Use of Suction to Control the Boundary Layer

35. If enough suction could be applied through a series of slots or a porous area situated at about the position shown in Fig. 9, separation of the boundary layer at almost all angles of attack could be prevented. However, it has been found that the power required to draw off the entire boundary layer so that it is replaced by completely undisturbed air is so large that the entire output of a powerful engine would be required to accomplish this.

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

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

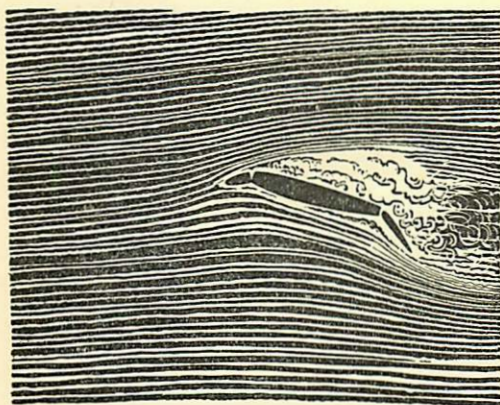
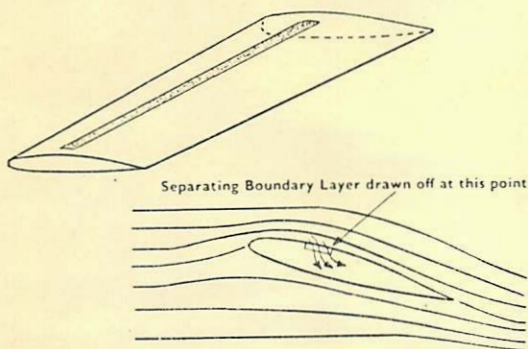
38. The suction is effected either through a slot or series of slots in the wing surface or by having a porous surface over the area in which suction is required. These devices are positioned at a point where the thickening effect of the adverse gradient is becoming marked and not at the beginning of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

Use of Blowing to Control the Boundary Layer

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

Effect of Boundary-Layer Control when Flap is Used

40. Very high maximum lift coefficients can be obtained by combining boundary-layer control



with the use of flaps. In this case the suction, or blowing, of air takes place near the hinge line of the flap. An average C_L max. for a plain aerofoil is about 1.5, for the same aerofoil with a flap it may be increased to about 2.5; when boundary-layer control is applied in the form of blowing or suction over the flap, the C_L max. may rise as high as 5 and more. When this figure is put into the lift formula under a given set of conditions it can be seen that the amount of lift obtained is greatly increased when compared with that from the plain aerofoil under the same conditions.

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



Fig. 9. Boundary-Layer Control

The picture on the left shows the airflow about a wing with leading- and trailing-edge flaps lowered but with no boundary-layer control. That on the right shows the great improvement obtained from the same wing when suction is applied behind the leading edge and air is blown at high speed over the flap. The marked increase in lift is shown by the pattern of the streamlines.

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