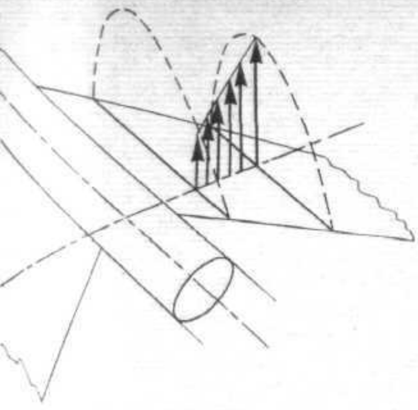

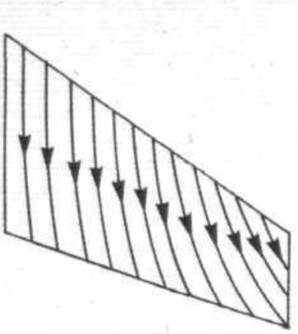

Fig 5 (left) Spanwise pressure-gradient on a swept wing; the vertical ordinates represent negative pressure, the shortest one representing the highest pressure. Fig 6 (right) Build-up of spanwise flow in the boundary layer over a swept wing

well be washed-out in this fashion anyway. In such a case the primary aim is to raise the M_{crit}-C_L boundary of the aircraft by spreading the load more evenly across the span (constant C_L); low-speed pitch-up improvements are a useful related side-effect. An extension to this concept may be used if design to attain constant C_L across the span results in substantial upward twist in the root region. With the help of some negative camber, if necessary (Fig 7), a high-incidence root can be made to stall at the same time as the tip; this maintains overall stability, although usable C_L may not be increased. An essentially similar effect may be employed if slats or flaps are used at the leading edge to give high lift at low speeds. In this case (e.g., VC10) the slat or flap is not continued right in to the root, which therefore stalls at high incidence as required.

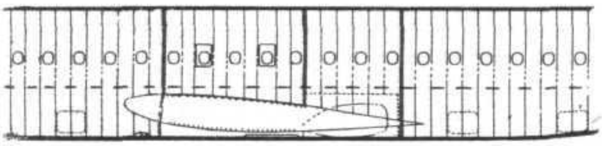

Fig 7 One of the most pronounced negative-camber wing root profiles is found on the Douglas DC-8. The section is almost a conventional aerofoil upside-down

Sweep being the other prime factor causing flow separation at the tip, it can be inferred that pitch-up might be delayed by decreasing the sweep over the outer wing. Such a modification was carried out on a number of aircraft (e.g., Swift and Javelin) in conjunction with, if necessary, a reduction in thickness/chord ratio to make good any loss in drag-rise Mach number. It also forms part of the philosophy behind the crescent wing, of which much was expected at one time. Reducing the sweep in this way certainly can have beneficial effects; for example, in reducing l_v, the rolling moment due to sideslip. However, as far as pitch-up is concerned, results have been rather disappointing in that the onset of separation, effectively delayed at the tip, begins to occur in the vicinity of the crank. Tunnel tests on the Supermarine 545 crescent-winged fighter suggested that an improvement at both high and low speeds would be obtained if the sweep on the outer panel were increased rather than decreased. The crescent wing as such seems to have disappeared from the scene; but its other chief characteristic, increased sweep at the root to raise M_{crit}, is still very much with us.

Once the tip has stalled the separated-flow region spreads forward and inboard as incidence increases. It is generally aggravated by downward deflection of the aileron, since this increases the effective camber of the rear part of the aerofoil and hence worsens the adverse chordwise pressure gradient; the reverse effect is also true in that the flow tends to stick when the aileron is raised, thus giving the aileron-reversal effect mentioned earlier. The use of spoilers for roll control obviates any such reversal or loss of effectiveness; inboard ailerons may also be used since, by virtue of their location, they avoid the separated-flow region. If outboard ailerons are retained their effectiveness can be improved, at the expense of a small base-drag penalty, if they are thickened to give a blunt trailing edge. This reduces the pressure gradient over the rear part of the aerofoil by reducing the curvature of the surface, but blunt ailerons are primarily to alleviate shock-induced separation which will be dealt with later.

For dealing with the type of separation already considered, the most familiar methods are perhaps the airflow fence and the vortex generator or turbulator, one or other (sometimes both) having been used on many swept-wing aircraft. Usually a single fence per wing is sufficient, situated at around two-thirds span (Fig 8), although other arrangements are frequently used. In addition to the more familiar outboard fence, the early Trident prototypes were experimentally fitted with a fence close to the wing root. This simply acted as a fairing at the inboard end of the drooping leading edge and was deleted when proved unnecessary. The outboard fence gives substantial benefits and has been retained on the Trident 1E and 1F, for which the drooping leading edge has given way to Krüger flaps inboard and slats outboard.

The action of a fence is rather more complex than a superficial examination suggests. Obviously, a fence across the rear part of the chord provides a physical barrier to the spanwise boundary-layer flow and, later, to the inwards spread of separation. Secondly, and particularly at high incidence, the local distortion of the flow due to a fence projecting well forward tends to cause the formation of a separated-flow region just inboard of the fence and a vortex just outboard. The flow separation is unlikely to spread and is therefore unimportant, except that the drag penalty may be substantial for a multi-fence installation, like that on the Mig-15 and Mig-17.

The vortex is generated from the free stream over the forward part of the fence, and can be quite powerful. It lies back across the wing upper surface, and acts as a kind of aerodynamic fence by sweeping away the boundary layer in that region. A very important additional effect is that the rotational speed of the air in such a vortex, when added to the normal chordwise component, gives an exceptionally high velocity over the wing surface beneath; hence the suction, and therefore the lift, in this region is increased, thus tending to compensate for the loss of lift in the separated-flow region outboard. A similar vortex, giving equivalent benefits, is shed from a discontinuity in the leading edge. Usually this is achieved by extending the wing chord forward over the outboard part of the wing, since the resulting reduced t/c ratio confers additional benefits at higher Mach numbers. The required vortex is then generated at the sawtooth junction so formed, and is sometimes reinforced by the addition of a short fence at the junction (Fig 9).

The vortex generator proper is usually a small vane, perhaps 1in to 2in high depending on the expected boundary-layer thickness in its neighbourhood. A series of these devices is fitted on one or more rows across the wing span, each vane inclined to the local airflow and usually toed-out on a swept or delta wing. Behaving like

Fig 8 An aircraft subjected to extensive development, the Hawker Siddeley Sea Vixen finally went into production with a dog tooth and single deep (but fairly short) fence at about two-thirds span on each wing. The leading edge outboard of the discontinuity is slightly drooped