Aircraft Flight

A description of the physical principles of aircraft flight

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fourth edition

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Fig. 4.14 Bent tips on the Aerospatiale Robin

It should be noted, that end-plates do not in fact destroy the trailing vortices, they merely modify the trailing vorticity in a beneficial way.

Sometimes, an end-plate effect can be achieved by ingenious design, as on the tailplane of the Optica, shown in Fig. 4.9. Auxiliary wing-tip fuel tanks and tip-mounted weapons can also have a marginal end-plate effect, as well as helping to reduce wing bending stresses.

Wing-tip sails or feathers

There are several wing-tip devices that have been shown to produce significant reductions in drag. One of these is the wing-tip sail shown in Fig. 4.15. This device has been around for millions of years in the form of the tip feathers on some birds' wings. At the tip of the wing, there is a strong upflow, as the air spills over from the underside. The feathers, or sails, are angled so that they generate a forward component of force, or negative drag, as illustrated in Fig. 4.16. For optimum effect, the feather angles need to be altered according to the flight condition. Curiously, quite a bit of research work had been conducted on this idea before anyone spotted that birds were already using the principle. It has been found that beneficial interference effects occur when

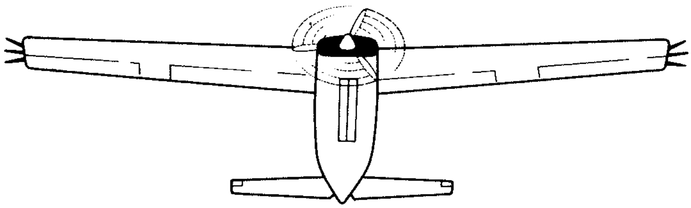


Fig. 4.15 Wing-tip sails or feathers can produce a significant reduction in drag

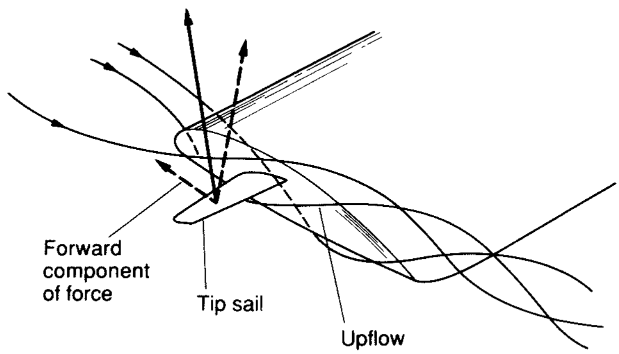


Fig. 4.16 A wing-tip sail
The sails are angled downward to take advantage of the upflow that occurs around the tip. The resulting force has a forward component. Normally three or more sails are used (*after Spillman*)

several sails (usually three) are used, as in Fig. 4.15. Birds also use several tip feathers; interestingly, always an odd number.

Winglets and other devices

At the time of writing, the most popular wing-tip device appears to be winglet, which may be seen on the Airbus A340 shown in Fig. 4.17.

As illustrated in Fig. 4.18, winglets take advantage of the strong sidewash that occurs at the wing tip. Due to the sidewash, the air flow meets the vertical winglet at an angle of attack, and thus a sideways force is generated. The winglet therefore has its own horseshoe vortex system, as shown in Fig. 4.18(a). At the wing-tip/winglet junction, the winglet vortex system partly cancels the wing-tip vortex, so that effectively, the main 'tip' vortex forms at

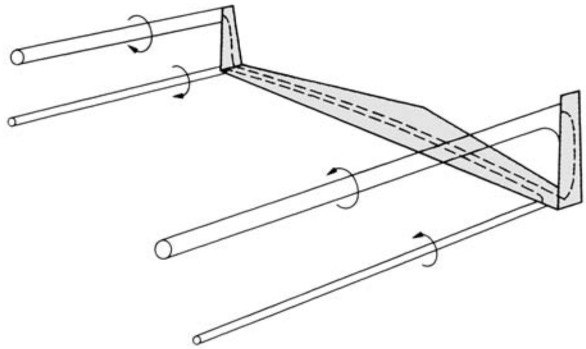
Fig. 4.17 Wing-tip winglets on the Airbus A340 reduce drag

the tip of the winglet. This vortex is above the plane of the main wing, and so its downwash effect is reduced. In fact, the winglet modifies the whole of the spanwise distribution of trailing vorticity in a way that reduces the downwash and induced drag. In addition, the sideforce on the winglet can have a forward thrust component, as shown in Fig. 4.18(b). This also contributes to the reduction in drag.

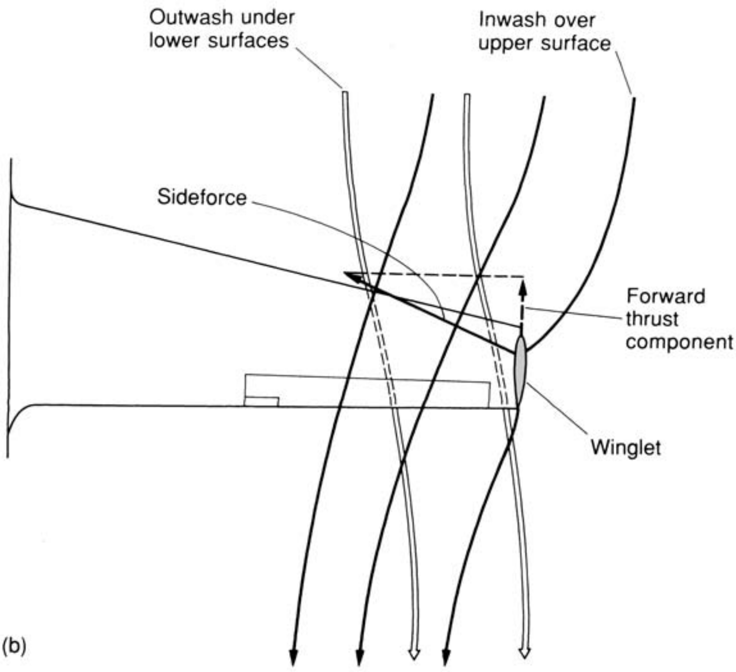
An inward sidewash occurs on the upper surface of the wing, as air is drawn in towards the low pressure. Conversely, an outward sidewash occurs on the lower surface, where air flows away from the high pressure. Thus, winglets can be fitted both above and below the wing tip. Because of the requirements of ground clearance, however, they are often only fitted above the tip.

There was some initial scepticism concerning the claimed advantages of such devices, because it seems to be a little like picking oneself up by one's bootstraps. However, theoretical study (Yates *et al.* 1986) shows that they do not contravene any of the laws of nature, and that significant reductions in trailing vortex drag are possible using such devices. These theoretical predictions are well supported by experimental evidence.

Devices such as winglets are described as non-planar, because the wing is not in a single plane. A full analysis of non-planar lifting surfaces is given in Yates *et al.* (1986). In general, theoretical analysis indicates that **for a given span**, there is a wide range of non-planar wing shapes that should give less



(a)



(b)

Fig. 4.18
(a) The winglets produce their own horseshoe vortex systems which partially cancel the main wing trailing vortices at the winglet/wing junction. The tip vortices are thus effectively pushed to the tops of the winglets where their downwash effect on the main wing is reduced (b) Plan view of a wing with a vertical winglet at the tip
The inwash effect over the upper surface produces a force on the winglet that has a forward thrust or negative drag component

trailing vortex drag than a simple elliptical planform wing. The monoplane with winglets, and the biplane are two examples. However, in many cases, including that of the biplane, unless there is some good reason for limiting the wing span, it is cheaper and easier to use a simple monoplane, and to reduce the drag by increasing the aspect ratio.

It should be noted that winglets will not significantly reduce the drag if added to a wing that has already been optimised for low drag. If winglets are to be used to full effect, the wing has to be designed to take account of their presence from the outset. They can also be used to reduce the drag of a wing which was not optimised for low drag.

Both sails and winglets modify the distribution of vorticity downstream of the wing, and generally inhibit the formation of a well defined vortex at the tip. This has been shown to be a useful side-effect for crop-spraying aircraft, as it prevents the spray from being lifted above the wing and blown off target by a cross-wind.

Although these devices modify the trailing vortex field in a way that has a beneficial influence on the trailing vortex drag, they do not destroy the trailing vorticity as is popularly believed. Spillman (1988) reports that in flight trials with wing-tip sails, the disturbance effects far downstream were, if anything, slightly increased.

Winglets and other devices can produce a low-drag wing, but they add to the cost and complexity of construction. They also modify the handling and stability characteristics. In one case tested, the cross-wind stability of the aircraft in landing was severely affected, and in another, interference with the flow over the ailerons produced a control reversal effect in some circumstances. Even though the influence on handling and stability may not be detrimental in all applications, the effects must be fully evaluated for certification purposes, and this can also be a costly process.

An ingenious use of winglets was made in the design of the Beech Starship (Fig. 4.10). Here, the winglet also served as the vertical fin, and is thus a necessary, rather than additional feature.

The modern use of composite construction makes it possible to design much more complex out-of-plane wing geometries, as on the Airbus A350XWB shown in Fig. 14.6.

In addition to the use of these fixed devices, drag reductions have also been obtained by using spanwise blowing (Tavella *et al.* 1985).

Drag due to interference effects

Any intersection between two surfaces such as at the wing–fuselage junction has a disruptive effect on the flow, and extra drag is incurred. Acute angles such as that formed between the wing and fuselage on either high- or low-wing aircraft are worse than oblique angles. A mid-wing position would be better from this aspect, but mid-wing designs introduce structural problems. The cabin crew in a mid-wing airliner might not take kindly to the main spar getting in the way of the drinks trolly.

On a low-wing aircraft, the fuselage can interfere with the pressure distribution on the upper surface of the wing, possibly inducing flow separation. A high-wing configuration is better in this respect, as in this case, the flow on the under-surface is the most affected. The under-surface flow is normally in a favourable pressure gradient, and is thus less likely to separate. The high wing arrangement has a number of disadvantages, however, including problems involved in trying to avoid long undercarriage legs, and adverse interference effects between the wing wake and the tailplane. Notice the very high mounting position of the horizontal tail surface on the C-17 (Fig. 10.20), and the BAe 146 (Fig. 6.26). This is necessary, in order to keep the tailplane out of the wake of the wing at high angles of attack.

The wing–fuselage interference effect is largely a manifestation of the gap in the spanwise lift distributing mentioned above (Fig. 4.11), and can be reduced by use of a lifting fuselage as on the MiG-29 (Fig. 4.12), where the interference effect is also reduced by use of a blended wing–fuselage. A blended wing–fuselage was also used on the SR-71 Blackbird spy-plane (Fig. 6.40). In this case, the arrangement has the important advantage that the elimination of sharp junctions reduces the aircraft's radar signature. Interference effects can also be reduced by means of wing fillets, but this feature is rarely found on modern aircraft.

A more radical solution to the interference problem is to remove most of the junctions by adopting an all-wing configuration as in the B2 'Spirit' (Fig. 4.19). Large slender-delta-winged aircraft lend themselves to a nearly all-wing configuration, and such an arrangement was considered at the early stages of the Concorde project. The idea was eliminated because it would have required a very large aircraft, in order to provide sufficient cabin depth, and would have introduced another set of novel features in an already revolutionary design. It was also realised, that passengers would react unfavourably to the idea of having traditional port-holes replaced by overhead fanlights.

The last item in the drag budget is the undercarriage. Despite the considerable added cost and weight of a retracting undercarriage, the benefits are so great, that fixed undercarriages are rarely used on anything other than small light aircraft. An interesting solution to the problem of undercarriages is that used on the Quickie shown in Fig. 11.9. The canard foreplane has pronounced anhedral, and also serves as the undercarriage legs. The Rutan Vari-Eze shown in Fig. 4.20 uses a retractable nose wheel which is also lifted for parking, as shown. Retracting the nose wheel saves a considerable amount of drag, and the pilot would probably get away with forgetting to lower it on landing; a common error with amateur pilots.