Do winglets work?

Steve Smith
from Pacific Soaring Council *West Wind*

WELL, in a word, yes. But don't they hurt high speed performance? Not necessarily. It seems I'm often discussing winglets with glider pilots. So I'd like to try to provide some technical framework for understanding what winglets do.

Sources of Drag First, in order to understand winglets, you need to understand drag. Airplanes have three primary sources of drag. The first source is often called parasite drag or profile drag, and this has to do with the skin friction created by airflow over the aircraft surface. The second source is called induced drag, which is a result of generating lift with a finite wing span – an infinite wing would be nice, but it won't fit in your trailer! The third drag source is caused by compressibility effects on aircraft that fly nearly as fast as the speed of sound, or faster. Except for John McMaster's *Altostratus*, we don't need to worry about compressibility drag. The primary effect of winglets is to reduce the induced drag.

Parasite drag is naturally affected by the amount of wetted surface area. It also depends on whether the boundary layer is laminar or turbulent – but that's another story. For now, you need to know that parasite drag increases in proportion to the square of the airspeed. This turns out to be sort of universal – most aerodynamic forces increase in proportion to the square of the velocity, because the ability of the air to produce forces is related to the kinetic energy in the flow:

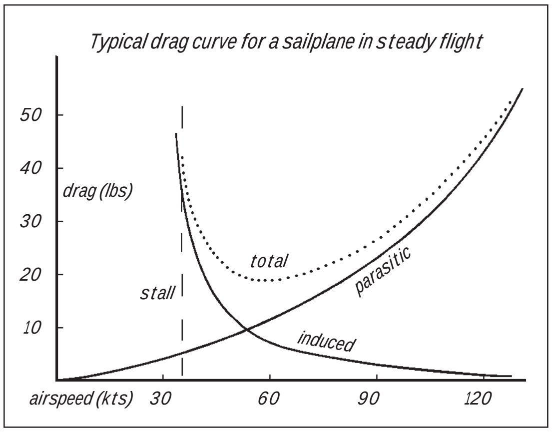
$$D_{parasitic} = k\mu V^2$$

Induced drag is a bit more complicated. A finite wing ends with a wingtip, where the higher pressure air under the wing can leak around the end and fill the low pressure area on top of the wing. This flow around the tip forms a vortex that trails off downstream. The flow around the tip also reduces the lift in the area near the tip by tending to equalize the low pressure above the wing. The vortex contains energy in the form of the swirling flow velocity. We call the force required to pull the wing along to produce these tip vortices "induced drag". The mechanism through which the wing "feels" the presence of the tip vortices is the downward velocity induced on the wing by the vortices. It is as if the wing is flying in a self-generated region of sink.

This concept is very oversimplified – a more realistic explanation requires a fair bit of math and physics. What really happens is that vorticity is shed all along the trailing edge, not just at the tip. The distribution of lift along the span of the wing determines how much vorticity is shed along the trailing edge. It can be proven that for a planar wing (no winglets), the induced drag is the smallest when the spanwise distribution of lift is shaped like an ellipse. This lift distribution produces the vorticity distribution with the minimum energy. In steady flight, induced drag varies in proportion to the square of the weight, and inversely with the square of the wingspan and velocity:

$$D_{induced} = k\mu(W / bV)^2$$

If the aircraft is heavier, it needs more lift, and so produces more induced drag. If the lift is distributed over a longer wingspan, the trailing vorticity is spread out more as well, dissipating less energy. If the aircraft flies faster, it produces the same lift with less angle of attack, less disturbance to the flow, and creates weaker vorticity in the trailing wake.


Typical drag curve for a sailplane in steady flight

For a given aircraft weight, the total drag is the combination of the parasite drag and the induced drag. Looking at the above diagram, you can see that a minimum drag point occurs where the parasite drag and the induced drag are equal. At lower speeds, the parasite drag is small, but the induced drag increases very fast. At higher speeds, parasite drag increases but induced drag becomes small. This trade-off between parasite drag and induced drag is what makes the design of winglets interesting.

How do winglets reduce induced drag?
Adding a winglet to a wing has a similar effect to adding wing span. By providing more length of trailing edge, the vorticity is spread out more for the same total lift, so the energy loss is less. The detailed interactions between the wing and winglet are a bit different than a simple span extension, but the effect is similar. In both cases, the induced downwash is reduced. A well designed winglet is equivalent to about half its height in span increase. At the same time, the winglet adds much less additional structural load to the wing than a tip extension does. Detailed studies of the combined structural and aerodynamic effects of winglets on transport aircraft show that they are not quite equal in overall performance to a simple span extension. Current conventional wisdom states that winglets should only be used in cases where there is some limiting constraint on wingspan. Applying these results to sailplane design would indicate that winglets should not be used on Open class sailplanes, but should be used on 15 metre and Standard class sailplanes.

What about high speed performance?
Looking at the figure, you can see that induced drag becomes unimportant at high speeds, whereas the parasite drag becomes dominant. A crossover point occurs where the induced drag benefit of the winglet is outweighed by the increase in parasite drag.

Here's a realistic example. Suppose a winglet is installed that reduces the induced drag by 10% and adds 1% to the parasite drag. At the speed for best L/D, where induced drag and parasite drag are equal, the net improvement would be 4.5% (.5 x .1 – .5 x .01 = .045). This amounts to about 6 ft/min for a typical 15 metre sailplane. At a speed of 1.73 times the best L/D speed, parasite drag is 90% of the total, and induced drag only 10%. At this speed, the net improvement is almost zero (.1 x .1 – .9 x .01 = .001). For a sailplane with a best L/D speed of 60 knots, the theoretical crossover speed for these winglets is 104 knots. Above this speed, these winglets degrade performance.

But overall cross-country performance is a balance between the low and high speed performance. Classical MacCready theory indicates that 50% of the time is spent cruising and 50% climbing. In this case, the break-even speed would occur where the disadvantage at high speed equals the advantage at low speed. Because the actual drag is much higher at cruise, we can't compare on a percentage basis. The comparison must be made based on actual sink rate. Since half the time is spent cruising, the break-even cruise speed occurs where the increased sink rate equals the reduced sink rate at low speed. In other words, how fast do you need to fly so that the sink rate with winglets is 6 ft/min greater than without winglets? For the example used here, this occurs at 2.3 x best L/D speed or 138 knots. It's pretty rare that your MacCready directed speed to fly would be this fast!

You might point out that as soaring conditions become stronger, the MacCready model doesn't apply: the fraction of time spent circling becomes much smaller. But that doesn't necessarily mean that the time spent flying slow (near best L/D) also becomes small. Efficient use of cloud streets still dictates flying slowly in good lift. So, suppose you never fly slower than 70 knots. At this speed, the winglets improve your sink rate by almost 4 ft/min. You would need to fly 118 knots in order for the winglet penalty to be 4 ft/min, negating the benefit. About the only situation where soaring speed is consistently high enough that winglets would actually hurt overall is ridge running. Even in ridge soaring, there may be long gaps to cross where the benefit of the winglets would offset any cruise penalty.

Can the same argument be applied to tip extensions?

Well, that depends on the structural limitations on the sailplane. First of all, for the same improvement in induced drag, a shorter span extension will be required (about half, right?) but the tip extension has more wetted area, so more parasite drag. This added area is needed to prevent the tip extension from stalling at low speed. The reason winglets don't need the same area to prevent stalling will be explained later.

Anyway, a tip extension equivalent to the winglet example might improve induced drag 11%, but add 2% in parasite drag. At the best L/D speed: .5 x .11 – .5 x .02 = .045 (once again). But there is a crucial assumption hidden in these examples. The comparison is made at constant weight. If you install your tip extensions, are you allowed to ballast the sailplane to the same weight? If so, then the example is still valid. Now compare the performance of this tip extension at 1.73 times the best L/D speed, where parasite drag is 90% of the total, and we find: .1 x .11 – .9 x .02 = -.007. So, now the tip extension that appeared to be equivalent at low speed degrades high speed performance 0.7% at the speed where the winglets still provide a 0.1% benefit. One way to explain this is to say that the tip extension reduced the wing loading. What is really happening is that the parasite drag was increased for the same weight. What if you must reduce the gross weight when you install the tip extensions? In that case, the tip extensions hurt even more. This also illustrates why high wing loading is so important for Open class sailplanes.

The results here depend on many assumptions, but they do challenge the conventional wisdom that winglets are not as good as tip extensions. One major difference between sailplanes and transport aircraft is the range of speeds over which they perform. Transport aircraft adjust their cruising altitude so that they cruise only slightly faster than the best L/D speed, but sailplanes are expected to perform well at almost twice the best L/D speed.

What about stall? I mentioned that tip extensions are prone to tip stall, but winglets are not. Two effects come into play here. First is that fact that as you scale down an airfoil, the critical angle of attack for stall is reduced. This is called a "Reynolds number effect". In essence, the basic character of the flow is affected by the size of the wing. To achieve the desired elliptical lift distribution, you would like to make the tip chord very small, but if the chord is too small, it will be prone to stall early. So, now you want to put a tip extension on the wing, and you still try to achieve that elliptical lift distribution, but the tip chord must not get too small. So, you maintain more surface area and compensate by reducing the airfoil camber or twisting the wing slightly to reduce the tip angle of attack.

The added wetted surface area increases the parasite drag. The second effect explains why winglets can have such a small chord (and therefore smaller wetted area) without stalling. As the sailplane slows down and the angle of attack increases to maintain the lift equal to the weight, the tip extension experiences the same angle of attack increase, but a winglet does not. The flow angle experienced by the winglet is determined by the strength and distribution of the trailing vorticity, which is indirectly influenced by the increased angle of attack. The net result is that the effective increase in angle of attack for the winglet is much less than the increase in angle of attack on the wing. So, the lift doesn't build up as fast on the winglet and the wing stalls first. In practise, this effect is exploited to reduce the wetted area of the winglet as much as possible to the point where, ideally, the wing and winglet would stall at about the same time.

Other good things about winglets

Aside from the performance improvement offered by winglets, there are other benefits. The most notable of these are the increase in dihedral, increase in aileron effectiveness, and the reduction of adverse yaw. The increase in effective dihedral improves handling in thermals. There is less need for "top stick" to prevent a spiral dive. The impression is that the aircraft "grooves" better in a turn. The increase in aileron effectiveness and the reduction in adverse yaw both come from the lift of the winglet when the aileron is deflected. When the aileron is deflected, there is less "tip loss" of the added lift. There is much less of an increase in the tip vortex strength, again because the vorticity is spread out along the longer trailing edge, and the tip is further away. As a result, adverse yaw may be eliminated. For heavily ballasted sailplanes, the increased control and safety offered by the winglets may be a big advantage, regardless of any improvement in glide performance.

Other bad things about winglets

One disadvantage that is not often discussed is the reduction in flutter speed. Classical flutter occurs when the natural frequency in bending and the natural frequency in torsion get too close together. The torsion frequency is always somewhat higher than the bending frequency. By adding weight above the plane of the wing, the torsional moment of inertia is increased, which reduces the torsion frequency of the wing. Of course, tip extensions also reduce flutter speed. Both can be compensated for by clever addition of balance weights to the wing, but this is a complex problem requiring sophisticated analysis.

Conclusion I hope I've answered more questions than I've raised. I'm happy to discuss winglets in more detail with anyone, feel free to contact me by email at *scsmith@mail.arc.nasa.gov* ❖

Steve Smith is a Senior Aerospace Engineer at the NASA Ames Research Center. A full discussion of winglet design concepts can be found in "free flight" 2/92 p6.