WINGLET DESIGN FOR SAILPLANES

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IN THE ONGOING QUEST for higher performance sailplanes, winglets have provided a means for improving the performance with only a modest price per L/D point gain. Winglets act to reduce induced drag and act to control the crossflow in the tip region of the wings in such a way as to improve the handling characteristics at the same time.

By introducing a vertical cambered surface at the tip, the downwash field behind the wing is spread horizontally by several inches. Since the induced drag is inversely proportional to the effective width of this downwash field, the winglet therefore acts to reduce induced drag by displacing the vortices outward. Presumably the greatest effect would be obtained by introducing a high lift large surface winglet which would displace more air outward and alter the circulation pattern in a more significant way. However, the design of winglets involves the compromise of maximizing the low speed improvement without sacrificing high speed performance. Pilots will not fly with winglets if they perceive any deterioration of high speed performance.

BACKGROUND

First use of winglets
Winglets for modern aircraft were first proposed by Dr. Richard Whitcomb, at NASA Langley in the mid–1970's. At that time, wind tunnel models and subsequent full size flight tests on a Boeing 707 commercial jetliner demonstrated a significant reduction in total drag at high lift coefficients.

After the publication of the design philosophy, numerous researchers in industry tackled winglet design with varying degrees of success. Most tried to use potential flow methods for predicting tip inflow angles and surface pressure distributions, however given the nature of the flow field at the tip, this has lead many investigators to the wrong conclusions.

Potential flow analysis seems to steer the designer in the direction of excessively large winglets, while experimental data suggests that large winglets pay a greater–than–predicted penalty in high speed performance. Since potential flow methods cannot accurately predict the vortex roll–up at the tip, or the influence of secondary flows on the boundary layer, these methods have not provided the complete picture of the effect of winglets on performance. Also, potential flow methods do not show the significant influence of the effect of the fore–aft position of the winglets.

Experience with sailplanes
In sailplane racing circles, winglets were tried and then dropped by a number of university flying groups (Darmstadt, Braunschweig), and

the French manufacturer Centrair. The overriding concern repeatedly expressed by racing pilots was that the winglets, although they were known to provide a significant gain at low speed, would detract from performance at the high speed cruise condition, with a resulting net loss or perhaps no achieved gain in overall performance.

This concern is justified since winglets act to reduce both induced drag and drag due to crossflow at the tip; however, at high speed neither of these effects are large and thus there is some speed at which the overall surface friction drag of the winglet exceeds the induced/interference drag reduction provided by the winglet. The graphs below show this effect with large winglets added to an ASW–19 at Braunschweig. Clearly the key is to provide a minimum drag surface which does not stall at circling speeds.

Prompted by interest from Dr. David Marsden at the University of Alberta, and my own successful experience a decade ago with a homebuilt HP–18, the challenge was struck to

design an efficient pair of winglets for a Nimbus III for the World championships in 1989 at Wiener Neustadt, Austria.

Marsden had proposed using an unusual double element winglet on the Nimbus III *(emulating the primary wing feathers of a soaring bird)* which was inspired by a successful version on Marsden's DG–200. His experiments had shown that he was obtaining a significant improvement in lift capability of a tip section fitted with winglets.

Experiments with dual winglets
The initial promise of dual winglets on the Nimbus III tips did not prove out in either flight tests or wind tunnel tests. Although a gain in lift was measured, the interference drag of the two lifting surfaces caused the airflow across the rear winglet to be separated at even modest lift coefficients. This resulted in the winglet not being effective at either high or low flight speeds. At speeds below 55 knots, the rear winglet would experience massive separation (seen with tufts); and at speeds higher than that, the winglet
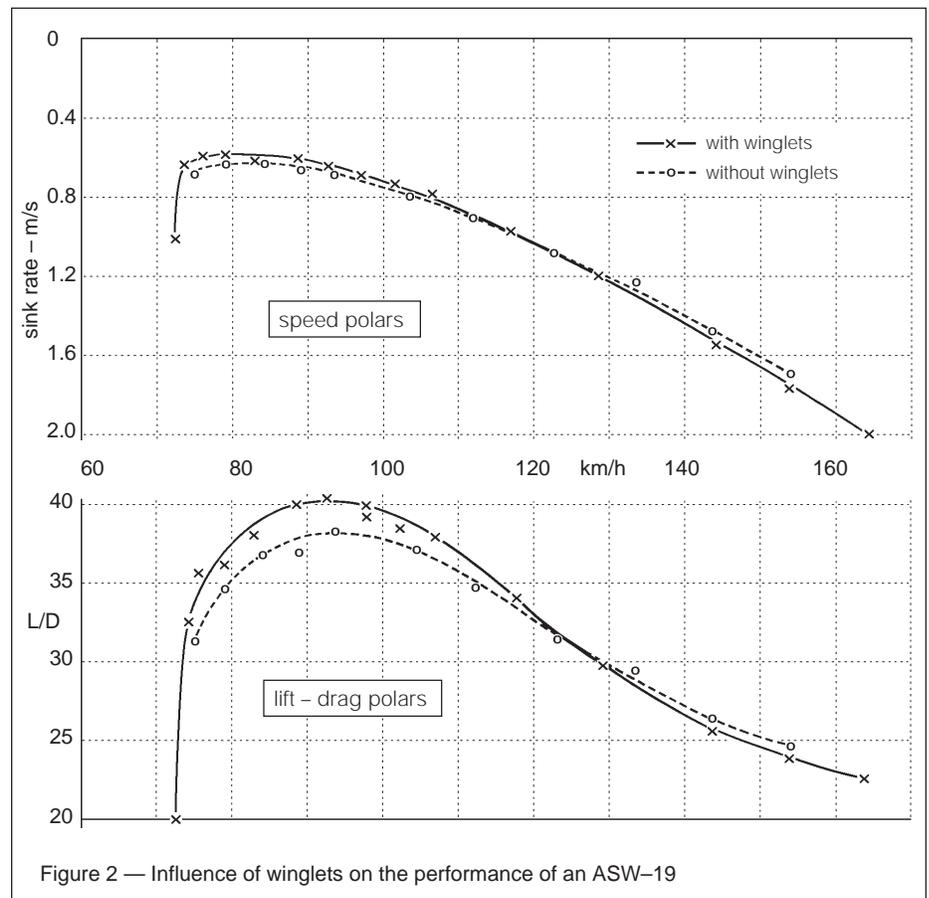

Figure 2 — Influence of winglets on the performance of an ASW–19

friction drag due to the highly cambered airfoils was so high as to cause an overall loss.

Second Iteration
The narrow tip chord of the Nimbus III (9 in) forced an abnormally low chord for the dual winglets (3–4 in). The resulting low Reynold's number of the winglet elements probably contributed to the separation problem and high drag. Thus it was evident that this design could be improved by going back to the conventional single element winglet. *(An airfoil's Reynold's number is related to its size — all else being equal, a small airfoil does not "work" as well as a large one. The R_e of a typical sailplane wing is 1,000,000. ed.)*

DESIGN OPTIMIZATION

Apart from the selection of a winglet airfoil, there were five key parameters that had to be chosen to optimize the design:

- Cant angle   • Twist distribution
- Sweepback   • Taper ratio
- Ratio of winglet root chord to sailplane tip chord

Cant angle
The selection of cant angle evolved from an unusual consideration specific to sailplanes: the narrow and highly flexible wings provide for a wingtip angle in flight which can approach 30 degrees on some sailplanes when flying with water ballast. A more common angle for modern 15 metre ships is 7–12 degrees.

On winglets that are nominally set to a cant angle of 0 degrees (at right angles to the wing), as the wing deflects, the winglet generates a sideload in flight which has a component oriented downward. This is a self defeating situation, since the winglet is generating additional drag by contributing to the weight of the aircraft. Thus a more reasonable approach is to set the winglets at least at a cant angle on the ground of 0 degrees plus the in–flight local tip deflection angle.

Sweepback
The selection of the sweepback angle was based on experimental observations. It was first believed that the sweepback angle for the winglet should be equal to that for the main wing (0 degrees), however experience proves otherwise. If a vertical winglet with no sweepback is built, it will be observed that the root of the winglet will stall first and that the tip will remain flying.

The optimum situation from an aerodynamic standpoint is to have the aerodynamic loading such that the entire winglet surface stalls uniformly. This can be achieved by sweeping back the winglet, which will increase the loading on the tip. Because of the rapid variation in angle of attack of the winglet as a function of height, a large degree of sweepback is required to load the tip correctly. For our winglets, a 30 degree leading edge sweep angle was used to achieve this effect.

Ratio of winglet root chord to sailplane tip chord
It would seem that the winglet might ideally be designed as an extension of the wing, and thus the optimum winglet would be a smooth transition of the wing from horizontal to vertical. Experiments suggest otherwise.

If the root chord of the winglet is equal to the tip chord of the wing, then the inflow angle at the tip will be less than when the winglet is a smaller fraction of the tip chord. The result will be that at high speed, the inflow angle may not be sufficient so as to prevent separation of the airflow from the outer (lower) surface of the winglet. Since other considerations require that a toe–out angle be set (about –3 degrees), it is desirable to allow some vortex induced flow to wrap around the wingtip and provide a positive angle of attack for the winglet at all flight speeds.

For the various winglets fabricated, the following ratios of root chord of the winglet to tip chord of the wing were used:

- DG–600   0.60   • Discus   0.70
- Ventus   0.57   • Nimbus III   0.95
- ASW–20   0.50

The choice of the root chord of the winglet is also constrained by the nominal tip chord of the wing, and by considering Reynold's number effects. Too small a winglet chord can result in extensive laminar separation and high drag. For the Nimbus III and Discus winglets, the small nominal tip chords force the winglet geometry to be smaller than would be desirable from a Reynold's number consideration.

Twist distribution
The twist distribution on a winglet is normally selected so as to provide a uniform load distribution across the winglet span. Since the inflow angle is higher at the base, the winglet is twisted to higher angles of attack toward the tip. This is opposite to the general design methodology for wings, which normally have washout (either geometric or aerodynamic) so as to decrease the angle of attack towards the tips.

The determination of optimum twist for our winglets was made by iterating experimentally. When flight tested, the first set of winglets fabricated stalled at the root first with a progressive stall developing upwards towards the winglet tip. By twisting the winglet to increase the angle of attack at the tip, the entire surface of the winglet could be made to stall simultaneously. Two degrees of twist from root to tip proved to be optimum.

The second benefit of positive twist on the winglet is that the high speed performance is enhanced — there is less likelihood of developing separation on the outer surface of the winglet at low inflow angles (high speed = low coefficient of lift, C_l).

Taper ratio
The effect of taper ratio on inflow angles and the resulting optimum twist distribution was analyzed theoretically by K.H. Horstmann in his PhD thesis. It was shown that as taper ratio increases, the optimum twist distribution for the winglet varies more linearly from root to tip. From a construction standpoint it is also easier and more accurate to build a winglet with a linear change in twist angle along the winglet span. This favours a winglet with a larger tip chord. We also want to try to maximize the tip chord so as to maximize the Reynold's number. Accordingly, a ratio of tip to root chord of 0.6 was selected.

Toe–out
The determination of toe–out was based on the simple consideration that we were trying to maximize the speed at which no further benefit is gained from the winglet, and thus select an angle of attack (α) setting for the winglet that will minimize the high speed drag.

Considering the C_l–vs–α prediction for the PSU–90–125 winglet airfoil, an angle of attack of –3 degrees corresponds to a C_l of 0. Given the fact that even at high speed there is a small inflow component at the tip, the winglet will actually be generating a slightly positive lift, even with the –3 degree root toe–out. Calculations show that when the wing is operating at a nominal lift coefficient of 1.0 (which corresponds to the circling lift coefficient), the lift coefficient of the winglet is 0.6 at the root and reduces to zero at the tip.

WINGLET AIRFOIL

The winglet airfoil was designed with the following criteria in mind:

- to minimize drag at low C_l conditions
- to design the winglet airfoil to be tolerant of low R_e
- to maximize tolerance to negative α

These design requirements are different than for a conventional sailplane airfoil. The resulting custom airfoil designed by Dr. Maughmer and Mr. Selig of Pennsylvania State University is shown in the figure below. Dr. Maughmer described the airfoil design philosophy as follows:

"The airfoil has the traditional undercamber removed from the lower surface trailing edge area, which minimizes the tendency to form detrimental laminar separation bubbles at low or negative angles of attack. At the price of a little C_{lmax}, which isn't important for a winglet anyway, the drag is lower than other sailplane airfoils everywhere up to C_l = 0.85, as well as

| 0 | 50 | percent of chord | 100 |

PSU–90–125 winglet airfoil
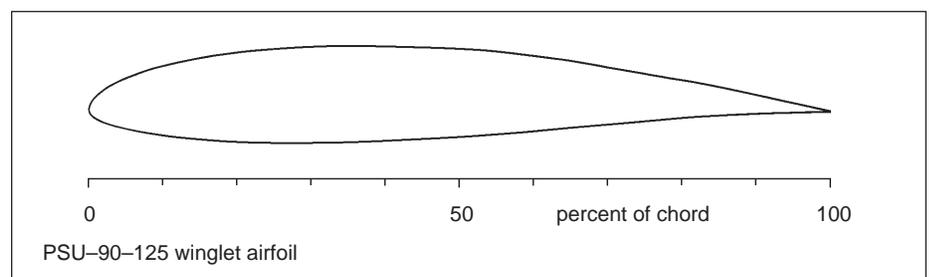
at negative C_l's, so that sideslips and horizontal gusts can be tolerated. The corners of the laminar bucket have been rounded to avoid unstable yawing moments that would be generated otherwise if the sailplane yawed to angles exceeding those corresponding to the sharp corners of the traditional Wortmann sailplane airfoils. Finally, the airfoil was designed to avoid laminar separation bubbles down to $R_e = 350,000$."

WING AERODYNAMICS

The change in the lift distribution of a wing with and without winglets is shown below. The boundary condition at the wingtip of the main wing no longer requires that the lift taper to zero at the tip. The assumed lift distribution for a wing with a winglet is assumed to terminate at an imaginary point equal to unfolding the vertical winglet in the horizontal plane. As a result the outer portion of the wing carries a higher load than it does without the winglet. Recent calculations on sailplanes with double trapezoidal planforms such as the ASW–20 or LS–6 suggest that this outer tip loading is more efficient from the standpoint of induced drag.

Secondly, the additional lift capability of the main wing means that the C_{lmax} of the overall wing is increased and the sailplane's circling performance will be enhanced.

Structural Loading
One of the key advantages of winglets is that they provide a performance increase while only fractionally increasing the root bending moment on the spar compared to a span extension. Whereas the moment arm of a span extension is one–half the semi–span of the wing (about 7.5 metres), the moment arm of a winglet is only equal to approximately one–half the vertical span (0.3 m) plus the deflected wing elevation at the tip. For sailplanes which are certified with tip extensions, one can be assured that the winglet will not overload the wing and all standard operating limitations will apply (Ventus, ASW–20, DG–600).
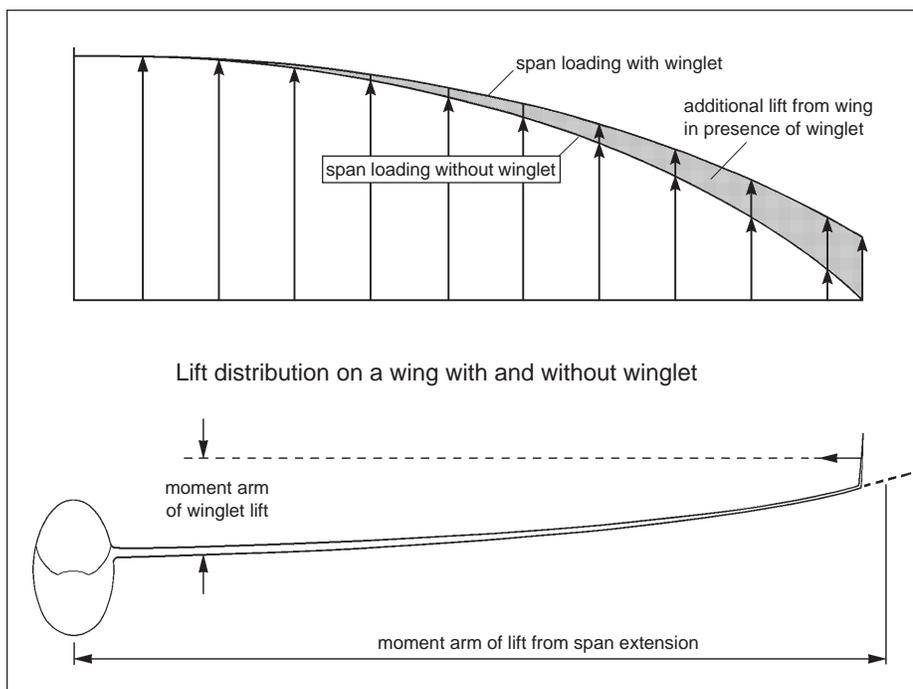
FINAL DESIGN

The final choice of design parameters is reflected in the design of the Ventus and ASW–20 winglets, which have been highly successful in competition. The ASW–20 winglet went through two iterations and the Ventus, three, before it was concluded that the design had reached a high level of refinement.

FLIGHT TEST RESULTS

Competition Results
The response of pilots flying with winglets in competition has been very positive overall. Certainly one of the measures of the success of the design is the fact that pilots after a period of evaluation have chosen to fly with the winglets. At the 1991 World contest in Uvalde, Texas, ten pilots chose to fly with our winglets – 8 Ventus, 1 ASW–20B, and 1 Nimbus III. At the end of the contest, a Ventus flying with our winglets had won four of twelve contest days and on the fastest day of the contest, the top five places in the 15 metre class went to sailplanes flying with our winglets. Additionally the trophy for the highest speed achieved overall went to Jan Anderson of Denmark, flying a Ventus with our winglets (his speed also exceeded the highest achieved in the Open Class). Two weeks prior, at the 15 metre Nationals in Hobbs, New Mexico, Reinhard Schramme from Germany established an unofficial record of sorts by flying his Ventus–C around a closed course of greater than 500 km with an average speed of 171 km/h (he would have won were it not for a photo penalty).

Bruno Gantenbrink and Hermann Hajek of Germany chose to retrofit winglets to their Ventus–C's and were delighted with the handling and performance qualities that they observed. Mr. Hajek noted as a particular advantage the improvement in his ability to maintain constant bank angle and speed with a full load of water. With winglets the effective dihedral is increased and the sailplane can be banked steeper while retaining control.

The dolphining performance is naturally improved with the winglets since they act to reduce induced drag while pulling positive 'g', and several pilots have perceived their sailplanes to have improved glide performance even at high cruising speeds in strong weather.

Flight Test Data
These positive results are confirmed by flight tests based on three high tows with each sailplane type which show the following performance gains as measured by the two–glider comparison technique.

ASW–20 flight test data: (pilots –Striedieck, Seymour)			
speed	duration	Δ with winglets	Δ ft/min
50 mi/h	5 min	+ 30 ft	6
65 mi/h	5 min	+ 7 ft	1.5
80 mi/h	2 min	+ 10 ft	5
100 mi/h	2 min	0	0

Ventus flight test data: (pilots –Mockler, Masak)		
speed (knots)	flap	Δ with winglets
40 dry, 53 wet	+2	9.1 ft/min
50 dry, 66 wet	0	9.0 ft/min
60 dry, 79 wet	0	9.8 ft/min
84 dry, 110 wet	–2	3.3 ft/min

Maximum performance gains with Masak winglets		
sailplane	winglet airfoil	L/D gain
ASW–20	NASA Van Dam	2.1
Discus	PSU–90–125	2.5
Ventus	PSU–90–125	3.5

CONCLUSIONS

The overall performance gains measured in free flight on sailplanes retrofitted with winglets are impressive and are supported by positive contest results. Handling qualities are improved in all cases, including improvement in roll rate and roll authority at high lift conditions.

The performance measurements have shown a higher gain in performance than would otherwise be predicted by conventional theory. It is believed that major benefits are derived from inhibiting the secondary flow that contaminates the boundary layer near the tip region. Prediction of this phenomenon requires computational power out of my grasp, and the present designs have been developed via experimentation and in–flight testing.

By August 1991, there were over forty–five sailplanes in the world flying with winglets designed and fabricated by the author. No negative reports or dangerous incidents (ie. flutter) of any kind have been reported. As a result of the positive service experience, Transport Canada have recently issued a supplementary type certificate for flight with winglets on the Ventus model, using JAR–22 as a basis for compliance. •

A bibliography is on page 13

Lift distribution on a wing with and without winglet

span loading with winglet

additional lift from wing in presence of winglet

span loading without winglet

moment arm of winglet lift

moment arm of lift from span extension