The Design of Winglets for Low-Speed Aircraft

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Abstract

Although theoretical tools for the design of winglets for low-speed aircraft were initially of limited value, simple methods were used to design winglets that gradually became accepted as benefiting overall aircraft performance. As understanding was gained, improved methods were developed, which ultimately resulted a number of successful applications of winglets. The current approach incorporates a detailed component drag buildup that interpolates airfoil drag and moment data across operational lift-coefficient, Reynolds-number, and flap-deflection ranges. Induced drag is initially predicted using a relatively fast multiple lifting-line method. In the final stages of the design process, a full panel method, including relaxed-wake modeling, is employed. The drag predictions are used to compute speed polars for both level and turning flight, yielding predicted performance that is in good agreement with flight-test results. These methods have been successfully applied to the design of winglets to improve the cross-country soaring performance of both span-limited and span-unlimited, high-performance sailplanes, as well as to improve various mission capabilities for several different categories of powered aircraft.

Nomenclature

b	span
c	wing chord
c_l	section lift coefficient
h	winglet height
C_{Dp}	profile drag coefficient averaged over span
K	induced-drag factor
S	planform area
V	airspeed
V_{CC}	average cross-country speed
V_{CR}	crossover speed
V_S	sink rate
W	weight
ρ	air density

Subscripts

W	wing
WL	winglet
WT	wing tip

Introduction

Over the past fifteen years, from initially being able to do little to improve overall sailplane performance, winglets have developed to such an extent that few gliders now leave the factories without them. This change was brought about by the efforts of a number of people to better understand how winglets work, to develop theoretical methods to analyze their performance, and to develop design methods that allow the benefits to be tailored such that gains in cross-country performance are achieved over a wide range of soaring conditions. The story of this development is an interesting case study in engineering design, in which trial and error, theoretical analysis, and flight testing all contributed to the successful solution of a difficult problem.

The efforts at Penn State to develop winglets for high-performance sailplanes began in the early 1980's as a collaborative effort with Mr. Peter Masak to design winglets for the 15m Class competition sailplanes of that era. Although work had already been done in the area of non-planar wings and winglets, in practice it was found winglets provided little or no benefit to overall sailplane performance.[1-4] The widely held belief at that time, essentially the same as that held for transport-type aircraft, was that while climb performance could be improved, it could not be done without overly penalizing cruise performance. Thus, it was with some skepticism that efforts were undertaken to work on this problem.

The first steps taken were directed toward the design of an airfoil specifically intended for use on a winglet. Although not a great deal was known at this time about exactly how a sailplane winglet should operate, it was clear that a winglet does not operate exactly as a wing and, consequently, an airfoil intended for use on a wing would not be a good choice for a winglet. Thus, the PSU 90-125 airfoil was designed. This was a robust design that was intended to operate over a broad range of conditions.

From this point, a trial-and-error process was begun that used flight testing as the primary method of determining the important design parameters. Although vortex-lattice and panel methods were of some value for gaining insight, they were unable to predict drag accurately enough to be of use in the actual design process. Likewise, because the beneficial influence of a winglet is due to it favorably altering the flow field over the entire wing, meaningful wind-tunnel experiments require a full- or half-span model. Thus, unless the wind tunnel has a very large test section, the high aspect ratios typical of sailplanes result in model chords that produce excessively low Reynolds numbers. To address these problems, methods of simulating full-scale flow fields with truncated spans have been explored but, in every case, the necessary compromises produce results that are somewhat questionable.[5] For these reasons, the parameters that were deemed the least important were set to reasonable values, while the more critical ones were determined from flight tests. Using some of the results from earlier work on winglets for transport aircraft,[6, 7] along with some simple calculations, the winglet height, planform, and cant angle, as defined in Fig. 1, were fixed. The goal from this point was to establish the spanwise load distribution on the winglet that would interact in a favorable way with the wing and thereby produce an overall drag reduction. Because the basic shape of this loading can be adjusted with either twist or sweep, the twist was set, again being guided by the earlier work on winglets, and the sweep iterated until the desired result was obtained. For minimum induced drag, if the planform is somewhat close to elliptical, the load distribution would have spanwise lift coefficients that are essentially constant. Thus, with the planform set, the sweep was adjusted until yarn tufts indicated a uniform stall pattern in the spanwise direction. The last design parameter to be determined was the toe angle. Because there seemed to be little benefit in having the winglet carry load beyond that of the wing, the toe angle was adjusted until both the wing and the winglet stalled simultaneously, again as determined with tufts.

Although it took some time and competition successes, the winglets that were the result of the process were the first ones that were generally accepted as beneficial to overall cross-country performance over a wide range of thermal sizes and strengths.[8] In 1989, one of these designs was adopted by sailplane manufacturer Schempp-Hirth and became the "factory winglet" for the Ventus. In retrospect, with the understanding that has come since, it seems that this process, while systematic and logical, was accompanied with a great deal of luck. It now seems somewhat remarkable that with the tools then at hand, it was possible to configure a winglet that actually worked!

Finite wing aerodynamics and winglets

In essence, the improvement in aircraft performance due to winglets results from their ability to reduce induced drag traded off against their added wetted area increasing the profile drag. Profile drag is the drag due to the shape of the airfoil or wing section. It is a consequence of both the skin-friction drag due to air moving along the surface of the airfoil, as well as pressure drag, due to pressures acting over the front of a body not being balanced by those acting over its rear. This pressure imbalance is the result of flow separating over the rear of the body, as well as total pressure losses in the boundary layer. To measure profile drag in a wind tunnel, a constant-chord wing using the airfoil of interest is made to span the width of the wind-tunnel test section. Thus, the flow is not free to come around the wing tips. As a consequence, the flow is two-dimensional. The absence of spanwise flow causes the wing sections to behave as though they belong to a wing of infinite span. Profile drag depends on, among other things, the amount of wetted area and the shape of the airfoil and its angle of attack. Profile drag increases with the square of the airspeed, V^2.

Induced drag is the drag that is a consequence of producing lift by a finite wing. In producing lift, there must be higher pressure on the underside of the wing than there is on the upper side. As this pressure difference "wants" to equalize, there is a flow around the wingtip from the high-pressure air on the underside of the wing to the low-pressure air on the upper side, as shown in Fig. 2. As depicted in Fig. 3, this results in spanwise flow on the finite wing that was not present on the infinite wing. This component of spanwise flow is present in the flow leaving the trailing edge, that from the upper surface flowing inboard while that on the lower surface outboard. At the trailing edge, these two streams meet with a spanwise component of velocity going in opposite directions. As a consequence, vorticity is shed from the trailing edge which, within a short distance downstream, rolls up into two well defined tip vortices.

Clearly, the generation of tip vortices requires energy and one approach to calculating the induced drag is through determining how much energy is contained in the trailing vortex system. This vortex system can be idealized as the "horseshoe" vortex system depicted in Fig. 4. As a consequence of producing lift, "an equal and opposite reaction" must occur. While there are many ways to describe the generation of lift, one is that the upward lifting force being produced requires that a certain amount of air be given a downward velocity, or downwash, as is indicated in the sketch. Thus, producing a given amount of lift is accompanied by the generation of a certain amount of downwash and as, a consequence, a certain amount of induced drag. To minimize this drag, the amount of energy used in producing the required downwash must be minimized, that is, the energy that is "wasted" in creating unnecessary spanwise flow and in the rolling up of the tip vortices must be minimized.

In observing the flowfield around the wing sketched in Fig. 3, it should be clear that the greater the span, the less the tip effect is felt on the inboard portions of the wing. That is, the greater the span, the more "two-dimensional like" will be the rest of the wing and, consequently, the less its induced drag. As the span is taken to infinity, the downwash and induced drag approach zero. Likewise, if the wing is not producing lift, there will be no downwash and thus no induced drag. Induced drag is a function of the inverse of the square of the airspeed, $1/V^2$, and the square of the span loading, $(W/b)^2$. Among other things, it also depends on the wing planform itself and how efficiently it produces lift with respect to induced drag. As a reference point, the most efficient planar wing is that having an elliptical loading.[17] Typical planar wings are somewhat less efficient, while non-planar geometries can be somewhat better than the elliptical case.

It has been known for over a century that an endplate at the tip of a finite wing can reduce the spanwise flow and thereby reduce the induced drag. Unfortunately, to be effective at this, the endplate must be so large that the increase in skin friction drag far outweighs any induced drag reduction. A winglet, rather than being a simple fence that limits the spanwise flow, carries an aerodynamic load producing a flowfield that actively interacts with that of the main wing to reduce the amount of spanwise flow. That is, the downwash (sidewash) produced by the winglet opposes the spanwise flow on the main wing. This effect has been measured experimentally and is shown in Fig. 5, where it can be seen that the spanwise flow has been largely eliminated by the presence of the winglet. In essence, the winglet diffuses or spreads out the influence of the tip vortex such that the downwash, and consequently the induced drag, is reduced. In this way, the winglet acts like an endplate in reducing the spanwise flow but, by carrying the proper aerodynamic loading, it accomplishes this with much less wetted area. Nevertheless, recalling the penalty of profile drag with increasing airspeeds, the designer's goal is that of gaining the largest reduction in induced drag for the smallest increase in profile drag.

The winglet design process

To obtain the desired results over the entire range of operation of an aircraft, it is necessary to design a new winglet for every application. The area, height, cant angle, sweep angle, twist angle, and the all important toe angle must be uniquely determined to achieve the desired performance goals. Thus, even though the trial and error process described resulted in a successful winglet, much remained to do in the development of tools and methods for analysis and design. Through the efforts of a succession of excellent students,[5, 9-11] a great deal has been accomplished at Penn State which has bettered this situation.

The first accomplishment of these efforts was the design and testing of a new airfoil. With a much better understanding of the operating conditions of a winglet, the PSU 94-097 airfoil was designed to have much less conservatism than its predecessor.[12] Following this, theoretical methods have been developed and validated through comparison glides and flight-test measurements. As a result, the design tools are now quite reliable and the products of these methods typically meet their design goals without modification.[13-15] Winglets have been designed for a number of sailplanes and powered aircraft, including those used on the Schempp-Hirth Ventus 2ax, shown in Fig. 6, and those under development for the Discus 2, presented in Fig. 7.

Crossover-point method

The first attempt to better quantify the winglet design process made use of what has been termed the crossover point on the sailplane speed polar. This point corresponds to the speed at which the flight polars of the aircraft without winglets and with winglets intersect or, equivalently, where the change in sink rate due to the winglets is zero. As noted, the profile drag increases as V^2, while the induced drag increases with $1/V^2$. Thus, the crossover point is a simple way to make the tradeoff between the profile-drag penalty and the induced-drag benefit. Below this speed, winglets are beneficial, while above it they are detrimental. The crossover point is the flight speed at which the benefit in induced drag due to winglets is equal to the profile-drag penalty, that is, when

$$\Delta D_{PROFILE} + \Delta D_{INDUCED} = 0$$

The more the induced drag can be reduced for a given increase in profile drag, the higher the crossover point and the more effective the winglet.

To understand the factors that determine the crossover speed, V_{CR}, an expression can be obtained by equating the increase in profile drag due to winglet height with the resulting decrease in the induced-drag factor

$$V_{CR} = \sqrt{\frac{2W}{\rho b}} \sqrt[4]{\frac{\Delta K(h)}{\pi \Delta h \bar{c} C_{Dp,WL}}}$$

where $\Delta K(h)$ is a function relating the reduction in the overall induced-drag factor to a given increase in winglet height, h. Originally, this function was estimated using results from earlier work.[6, 7, 10] The lower the profile-drag coefficient of the added winglet area, $C_{Dp,WL}$, and the greater the span loading, the higher the crossover speed, whereas increasing the winglet height reduces it.

This simple expression for V_{CR} gives insight into how the crossover point can be controlled through the geometry of the winglet. In the early stage of development, the crossover point was simply set to be higher than the cruising speed corresponding to the strongest thermal strength anticipated. The use of this expression resulted in winglets that generally improved overall performance and, although based on a simple concept, was as accurate as the somewhat crude ability to predict the changes in induced drag due to changes in winglet geometry.

Modified crossover-point method

As the ability to predict the induced drag for a given wing geometry improved,[5, 9] the crossover-point method was modified. Rather than equating the change in profile drag with the change in induced drag in terms of winglet height only, the expression is written more explicitly in terms of parameters describing the winglet geometry and the resulting aerodynamic influences as

$$\left(SC_{Dp}\right)_{WL} - \left(SC_{Dp}\right)_{WT} + \frac{4W^2}{\pi \rho^2 V_{CR}^4} \left(\frac{K_2}{b_2^{\,2}} - \frac{K_1}{b_1^{\,2}}\right) = 0$$

where the "*WT*" subscript corresponds to the wingtip region that is removed to mount the winglet, the subscript "*1*" to the original wing, and "*2*" to the one modified with winglets. The weight of the aircraft, W, is considered to be unchanged by the wingtip modification. For restricted span classes, of course, $b_1 = b_2$. The problem for the winglet designer is to minimize the profile-drag increase due to adding the winglet, to maximize the drag reduction resulting from removing the original wingtip to mount the winglet, and to achieve the greatest induced-drag reduction by making the induced-drag factor, K_2, as small as possible relative to K_1. Likewise, the net area increase should be minimized, as should the profile drag coefficient corresponding to any added area. While this expression does not capture all of the details of winglet design, it does capture the essence.

Using either of the closed-form relations presented to guide the winglet design, a traditional drag buildup was performed to predict aircraft speed polar. Then crossover speed is adjusted, primarily using the toe angle, to allow the winglet to benefit performance over some part of the operational speed range. Shifting the crossover speed not only affects the speed range over which a benefit is achieved, but also the magnitude of that benefit across the chosen range. Shifting it to higher speeds reduces the performance gains due to the winglet at lower speeds, whereas shifting it to lower speeds achieves a much larger drag reduction, but only over a small portion of the flight polar.

A number of winglets were designed, fabricated, and flight tested using this method, and while based on simple ideas, these efforts contributed to the basic understanding of winglet design. First, whether it be with up-turned tips or winglets, it is beneficial for the design to be "out-of-plane." Second, while a great deal of work has been directed toward determining the optimum geometries for minimum induced drag,[9, 16] experience has shown that too much emphasis on this optimum penalizes the profile drag far more than can be offset by the induced-drag reduction.[13-15] The design goal is to minimize the overall drag, not just one component of it. For example, the optimum loading for minimum induced drag must be continuous across the juncture between the wing and the winglet, which requires the chords at the juncture to be the same, or that the lift coefficient at the root of the winglet to be proportionally greater than that of the wingtip. Either way, the amount of wetted area or the increase in lift coefficient results in profile drag that is considerably greater than that of current designs. Thus, although not optimal with respect to minimizing induced drag in accordance to classical theory,[16] winglets as currently designed achieve most of this reduction, and do so with a much lower profile drag increase than would otherwise be the case. In short, much of the optimal induced-drag reduction predicted theoretically is obtained by adding winglets to the wing. Once this is done, minimizing the profile drag of the winglet is paramount.

Present design approach for high-performance sailplanes

Many of the comments on winglet design presented thus far are applicable to any low-speed aircraft, while the details of the design methodology depend to a large extent on the particular mission of the intended aircraft. In the case of high-performance sailplanes, the broad nature of the mission profile greatly complicates the choice of an optimum crossover speed. In weak conditions, gains in climb offset losses in cruise. Conversely, in strong conditions, not penalizing high-speed cruise is of the most importance to overall cross-country performance. While the crossover-speed method is effective for predicting the change in aircraft performance due to the addition of winglets, and it does ensure some benefit, its use will generally not produce the best design. For high-performance sailplanes the optimal configuration cannot be determined without specifically taking into account the impact of the winglets on the average cross-country speed. To do this, a fast, accurate prediction of the aircraft performance has been developed and combined with a sailplane cross-country performance model, allowing the calculation of MacCready average cross-country speeds for specific weather conditions and aircraft configurations.[11, 13, 15] These average cross-country speeds are then used as the metric to determine the suitability of a design. This approach allows the entire flight profile to be taken into account in the design and yields a simple result encompassing the broad range of contributing factors.

Previous methods were not able to accurately and rapidly account for small changes in an aircraft configuration. The simplifications typically used, such as approximated airfoil characteristics and parabolic flight polars, introduce errors that are of the same order as the improvements due to winglets. While useful for exploring trends and the basic characteristics of winglets, these methods are not accurate enough for design.

Performance prediction

The calculation of sailplane performance is a major component of the winglet design problem. The performance evaluation must have sufficient resolution to account for the effect of changes to the winglet geometry. Because these effects can be relatively small and errors or inconsistencies in other portions of the calculation can overshadow them, it is important that all aspects of the performance calculation be accurately determined. The accuracy necessary for successfully undertaking activities such as winglet design is obtained through the use of a performance program that has been developed to predict the straight- and turning-flight polars of sailplanes.[11, 13-15] In addition to the drag contributions of the major components of the sailplane, the program accounts for the effects of airfoil characteristics, trim drag, static margin, flap geometry, and flap-deflection scheduling. The most important element of the method is the analysis of the wing-planform aerodynamics.

Essential to the analysis method is the interpolation of the airfoil data. Wing profile drag is such a large portion of the overall drag that small errors in its determination can eclipse the effects of winglets. To accurately provide such data, it is necessary to interpolate the airfoil drag and moment data over the operational ranges of lift coefficient, Reynolds number, and flap deflection.

The other essential component for predicting the planform aerodynamics is the determination of the span efficiency and lift distribution. The lift distribution directly affects the wing profile drag, and the planform efficiency dictates the induced drag of the wing. Because this is where the benefit of the winglet is quantified, an accurate method of determining these two items is of critical importance. In the present approach, use is made of both a multiple lifting-line method and a three-dimensional lifting-surface panel code. The multiple lifting-line method, which has been integrated directly into the performance program, has several chordwise lifting lines, each having a second-order vorticity distribution.[2] This produces a continuous sheet of vorticity that is shed into the wake. The method allows the spanwise lift distribution and induced drag of non-planar wing geometries to be predicted with reasonable accuracy and less computational effort than is required by a three-dimensional panel method. Although not accounting for the consequences of thickness and a free wake, the multiple lifting-line procedure is able to quantify the effects of winglets. For initial design iterations, the increased speed of the multiple lifting-line method more than offsets the small loss in accuracy.

For the final detailed design of the winglet, use is made of a panel method program that takes free-wake effects into account.[9] For the calculation of induced drag; the program applies the Kutta-Joukowsky theorem at the trailing edge.[17] This eliminates some of the problems associated with attempting to account for wake relaxation in the far field using a Trefftz-plane approach. While the differences in results between a relaxed wake and a fixed wake analysis are generally small, these differences can be important in determining the final winglet toe and twist angles.[5]

The turning-flight performance of the sailplane is obtained by adjusting the straight-flight polar for bank angle and load factor. By these means, the minimum sink rate, optimal bank angle, and optimal flight velocity as a function of turning radius are determined. The effects of deflected ailerons and the curved flow field are neglected.

Analysis of cross-country performance

With straight- and turning-flight polars available, an analysis of crossover speeds is possible but, as mentioned previously, a more rigorous means of evaluating designs is desirable. This task is accomplished with a program that calculates the MacCready average cross-country speeds for a given configuration using the straight- and turning-flight polars generated by the performance program.[11, 13-15]

The thermal model used in this analysis has a distribution of vertical velocity that varies parabolically with thermal radius. Thus, the thermal profile is specified in terms of the magnitude of the vertical velocity of the rising air at the core and the radius. The thermal profile has a significant impact on the cross-country performance of a sailplane, and the most realistic performance index would result from some particular mix of thermal strengths and profiles. This could be done, but instead a single, representative thermal profile is used here, as this greatly simplifies the interpretation of the results while still yielding a meaningful comparison between sailplanes having different winglet geometries.

To obtain the optimal climb rate for a particular configuration, the thermal profile is superimposed over the predicted turning polars. The straight flight polar is then searched for the inter-thermal cruise speed to optimize the MacCready cross-country speed. The result is a trade-off of climb and cruise performance, properly weighted to account for the variations in soaring conditions over which the sailplane might be operated.

Cross-country performance gains: a case study

To see the performance increases that are possible with winglets, the predicted speed polars for the Schempp-Hirth Discus 2, with and without winglets, ballasted and unballasted, are shown in Fig. 8. Although gains are demonstrated, they are difficult to assess because of the scales used on the polars shown. Thus, these data are replotted in terms of *L/D* verses velocity in Fig. 9. In addition to demonstrating the gains in carrying water ballast at higher cruising speeds, the benefit of winglets can now be seen. To get an even better idea of the gains in *L/D*, in Fig.10 these data are again replotted in terms of the percentage increase in *L/D* relative to the unballasted and ballasted glider without winglets. It should be noted that this winglet is such that the crossover points occur at airspeeds that are above the maximum allowable. As already noted, the crossover point that was so important in earlier winglet designs is no longer a factor in current designs. This is because experience has demonstrated that even though better overall performance could be achieved using the crossover point concept, this approach can result in a very large performance penalty if the winglets are operated much above the crossover speed. The problem is that during inter-thermal cruise in very strong conditions, there are strong psychological and strategic reasons for a pilot to “stay with the pack.” Unfortunately, the glider with winglets suffers a very large performance penalty for flying faster than the crossover speed, which the glider without winglets does not. Thus, as is typical of the more recent designs, for this design there are no allowable flight conditions at which the winglets penalize performance. While the percentage gain in *L/D* does not appear to be very great, it is a gain that comes without any penalty at higher speeds.

The influence of winglets on the percentage change in average cross-country speed relative to that of the baseline aircraft, that is without ballast and without winglets, is presented as a function of thermal strength in Fig. 11. The winglets improve the cross-country performance for all the thermal strengths considered, that is, for thermals having a 150 m radius and strengths, averaged across the diameter, of up to 6 m/s. As expected, the performance gain due to winglets on the unballasted glider is very significant for weak thermals as the winglets allow for some climb rate, whereas without winglets, it is minimal or zero. As the thermal strengths increase, the benefit due to winglets decreases; however, for this glider winglets do not hurt cross-country speed even for average thermal strengths of more than 6 m/s. The point at which full water ballast becomes beneficial is indicated by the crossing of the unballasted and ballasted curves at an average thermal strength of just above 4 m/s, corresponding to a climb rate with full ballast predicted to be about 2.7 m/s. As indicated, ballast causes a reduction in average cross-country speed for average thermal strengths of less than 4 m/s. For thermal strengths greater than this, winglets improve the cross-country speed, but only by a half-percent or so. The glider with winglets, however, can carry ballast to slightly weaker conditions without penalty than the glider without winglets can.

Other considerations

In designing winglets for a variety of sailplanes, as well as for a few non-sailplane applications, it seems to be true that all wings can be improved with winglets, although the better the original wing from an induced drag standpoint, the smaller the gain possible with winglets (and the more difficult is the design process). The case presented here, in fact, represents one of the smallest gains due to winglets thus far achieved. It is sometimes heard that winglets were tried on “such and such” a glider but did not work. What this actually says is that a poor design did not work. As an example of how critical some of the design issues can be, the effect of the winglet toe angle on the Discus 2 winglet design is presented in Fig. 12. Obviously, a small deviation from the optimum can cause the winglet to become a speed brake. Furthermore, as such parameters are unique to each type of glider, each glider must have winglets specifically designed for it. Rules of thumb regarding winglet design can be disastrous. It is certainly true that it is much easier to make a glider worse with winglets than it is to make it better!

In some cases, it has been found that the winglets fix some problem with the original wing. For example, in the case of a flapped glider, it is important that the flaps/ailerons extend to the wingtip. Otherwise, when the flaps are deflected upward for high-speed cruise, the tips are loaded far more than they should be for the optimal spanwise loading. Although only a small portion of the wing is seemingly influenced, it results in very significant induced drag increase. In these cases, cutting the tip back to the aileron in order to mount the winglet can result in gains, especially at high speeds, that would not be expected by the addition of winglets. In addition, it should be noted that although the current generation of Open-Class gliders still benefit from tip treatment, unless the wing loadings can be increased dramatically, increasing spans eventually reach the point where the penalty of any wetted area addition cannot be overcome by an induced drag benefit. This is true whether the additional area is due to a span increase or a winglet. Nevertheless, because of the fact noted that a winglet can achieve a given reduction in induced drag with less wetted area than a span extension, it has been the case that if a span extension benefits performance, then it is benefited even more if a winglet is added to the extension.

From the understanding of how winglets achieve an induced drag reduction, it also becomes clear that they can yield other performance and handling qualities gains as well. In particular, it has been found that winglets improve the flow in the tip region and thereby improve the effectiveness of the ailerons. This is in part due to the local angle of attack in the vicinity of the ailerons being reduced less by the reduced downwash velocities, as well due to the reduction of spanwise flow, helping to keep the ailerons effective. One of the benefits of greater control effectiveness is that smaller aileron deflections are required for a given rolling moment. This not only results in less drag for a given roll rate, but it also allows for the achievement of higher roll rates. Likewise, woolen tufts attached to glider wings have shown that much of the flow separation that is observed over the inboard tip during turning flight is essentially eliminated by the presence of a winglet. In addition to the resulting reduction in drag, winglets benefit safety in that the ailerons now remain effective much deeper into a stall than before.

Closing comments

Although the performance gains achieved with winglets are only a few percent at moderate thermal strengths, such small differences can be an important factor in determining the outcome of many cross-country flights or contests. For example, in a recent U.S. Open Class Nationals, less than 1.5% of the points awarded to the first-place competitor separated the first six places, far less than the performance advantage that can be achieved using winglets.

So, since their shaky introduction many years ago, the acceptance of winglets is now widespread. Shortly after their introduction to sailplane racing, only 19 of the 105 gliders competing at the World Championships in Uvalde, Texas in 1991 used winglets. At the present time, sport and racing sailplanes in almost every class make use of winglets or some type of tip treatment. Thus, after over a decade of winglets being applied to sailplanes, it is clear that the benefits are far reaching. If properly designed such that the profile drag penalty is of no consequence over the range of airspeed at which the glider is flown, then there seems to be no reason whatsoever not to take advantage of the performance and handling qualities benefits that winglets offer

Finally, although some of the spinning characteristics of gliders with winglets have been explored, the testing has not been extensive. The anecdotal evidence, however, generally indicates that gliders with winglets are more reluctant to spin, but once they do, the altitude required for recovery is somewhat greater than for the glider not equipped. Given the large number of glider fatalities that are a consequence of stall/spin accidents during approach, for which the altitude required for recovery is already insufficient, a question worth pondering is whether or not even the most basic training gliders might benefit from the installation of winglets.

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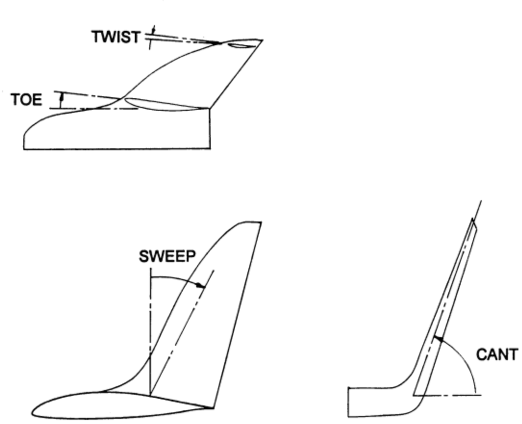

Figure 1 Geometric quantities used to define a winglet.

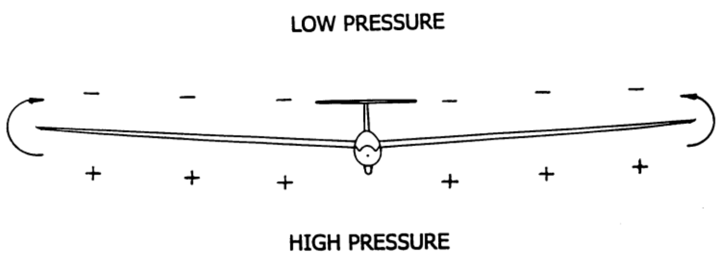

Figure 2 Higher pressure air on the wing lower surface flowing around wingtip to upper surface.

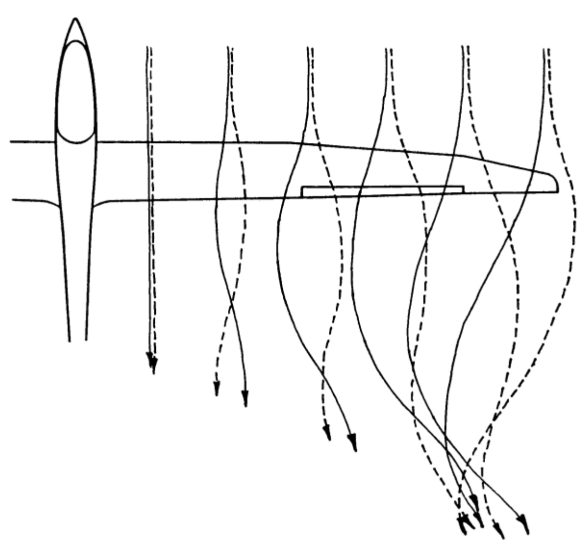

Figure 3 Spanwise flow on a finite wing - solid lines, upper surface; dashed lines, lower surface.

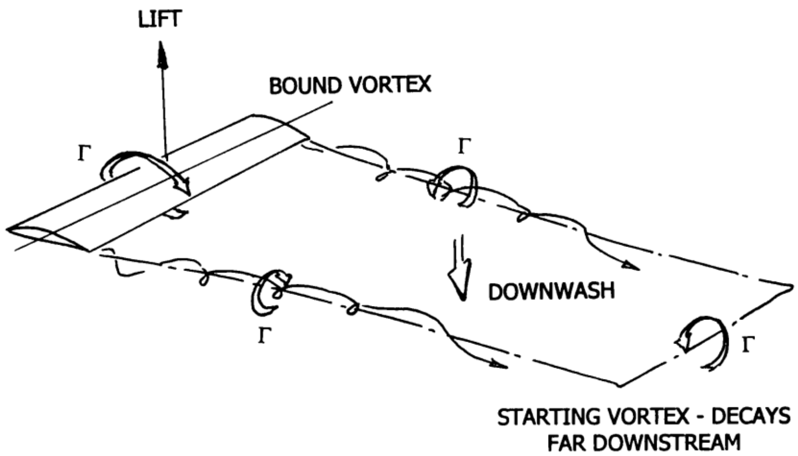

Figure 4 Idealized "horseshoe" vortex system.

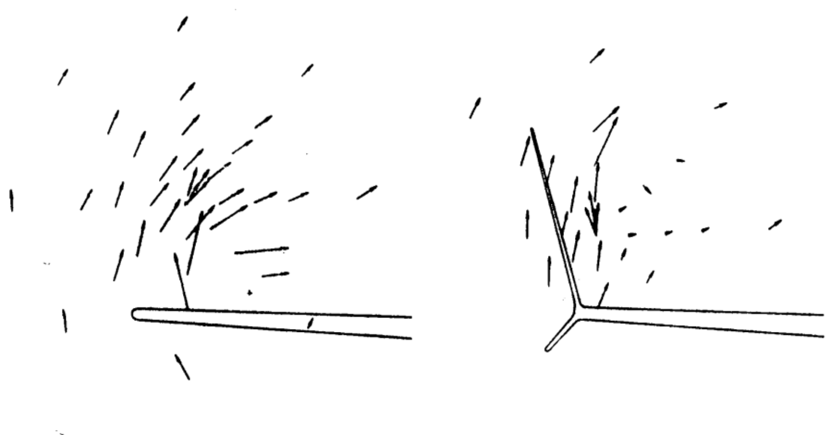

Figure 5 Experimentally determined flowfield crossflow velocity vectors behind model with and without winglets.[6]

Figure 6 Schempp-Hirth Ventus 2ax sailplane with winglets.

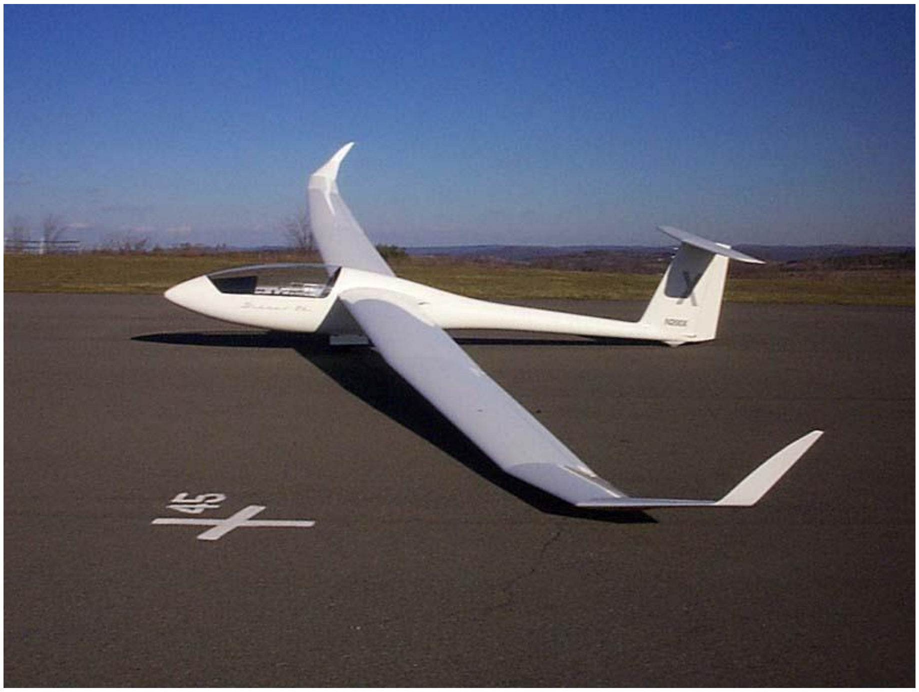

Figure 7 Experimental winglets on a Schempp-Hirth Discus 2 sailplane.

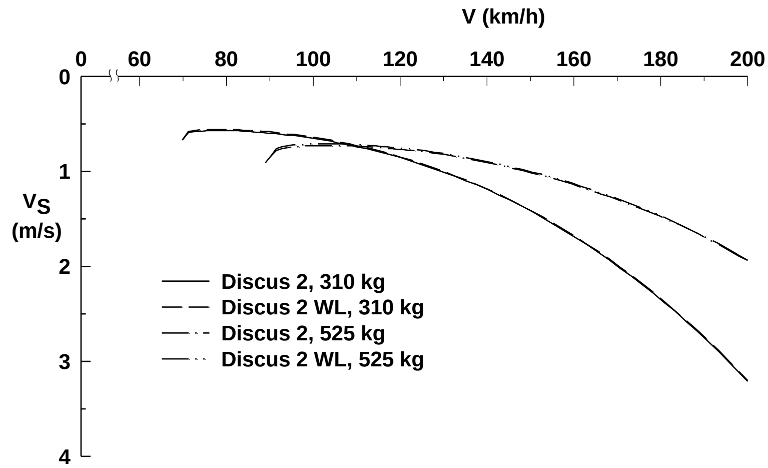

Figure 8 Predicted straight flight polars of unballasted and ballasted Discus 2, with and without winglets.

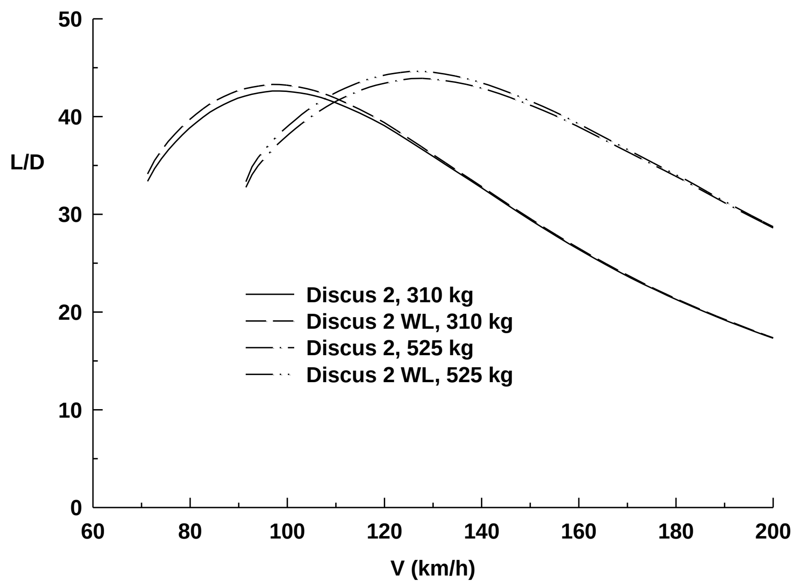

Figure 9 Comparison of predicted lift-to-drag ratios for unballasted and ballasted Discus 2, with and without winglets.

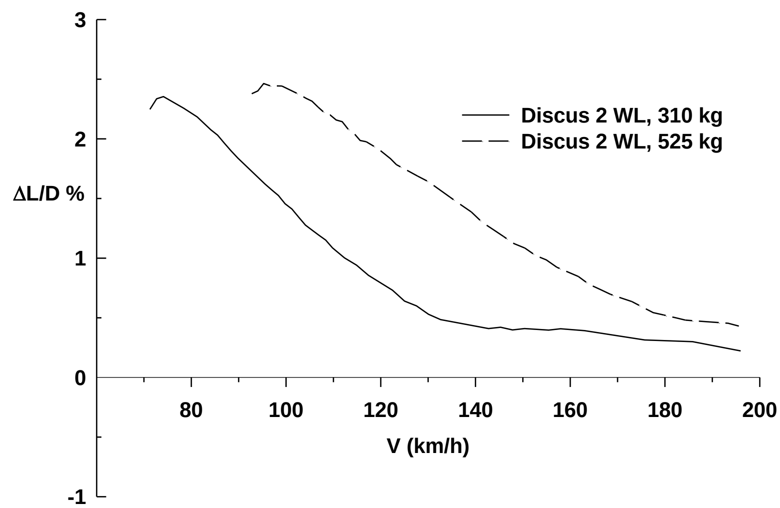

Figure 10 Percentage gain in predicted lift-to-drag ratios due to winglets for unballasted and ballasted Discus 2.

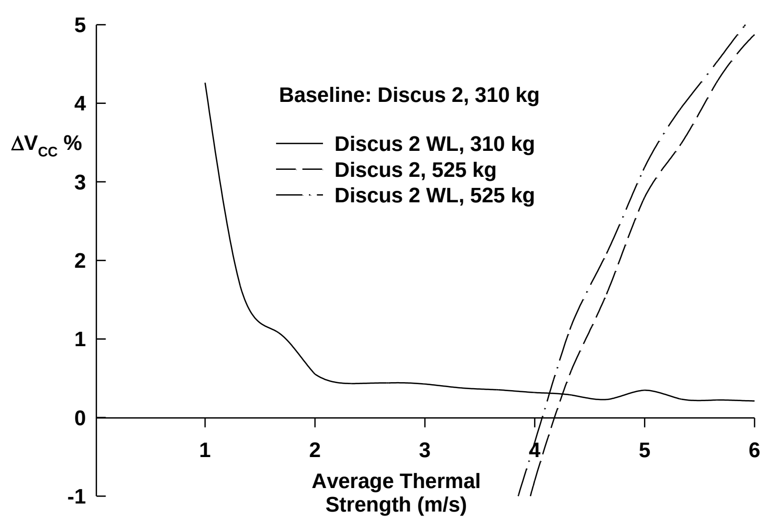

Figure 11 Percentage gain in predicted average cross-country speed due to winglets and ballast relative to unballasted Discus 2 (310 kg) without winglets.

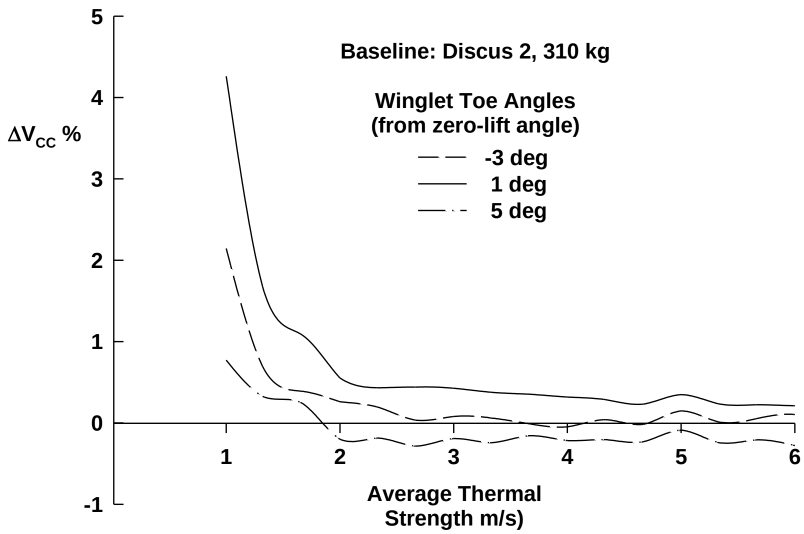

Figure 12 Percentage change in predicted average cross-country speed as it depends on winglet toe angle for an unballasted Discus 2. Toe angles are measured relative to the zero-lift angle of attack.