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THE DESIGN OF WINGLETS FOR HIGH-PERFORMANCE SAILPLANES

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Abstract

Although theoretical tools for the design of winglets for high-performance sailplanes were initially of limited value, simple methods were used to design winglets that gradually became accepted as benefiting overall sailplane performance. To further these gains, an improved methodology for winglet design has been developed. This methodology incorporates a detailed component drag buildup that includes the ability to interpolate input airfoil drag and moment data across operational lift coefficient, Reynolds number, and flap-setting ranges. Induced drag is initially predicted using a relatively fast multi- 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. The predicted performance is in good agreement with flight-test results. The straight and turning flight speed polars are then used to obtain cross-country performance over a range of thermal strengths, sizes, and shapes. Example design cases presented here demonstrate that winglets can provide a small, but important, performance advantage over much of the operating range for both span limited and span unlimited high-performance sailplanes.

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 velocity
V_S	sink rate
W	weight
ρ	air density

Subscripts

W	wing
WL	winglet
WT	wing tip

Introduction

From initially being able to do little to improve overall sailplane performance, winglets have developed to such an extent over the past ten years that few gliders now leave the manufacturers 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 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.

Although compared to other modern flight vehicles, the high-performance sailplane appears to be relatively simple, the design of such aircraft to maximize average cross-country speeds in any given weather situation is quite challenging.[1] This is largely due to the fact that in flying cross country, the sailplane must be able to climb effectively in thermals at low speeds, as well as being able to glide efficiently between thermals at high speeds. Thus, a successful design must balance the conflicting requirements of climbing and cruising over a broad range of possible soaring conditions.

For efficient climbing, a sailplane must be able to circle and maneuver with a low sink rate in thermals that can change dramatically in strength, size, and shape from day to day, and possibly even over the duration of a single flight. As this requires turning flight at low speeds and high lift coefficients, the reduction of induced drag is a major consideration in the design process. Clearly, although it can penalize the efficiency in cruising flight, the most straightforward method to reduce induced drag is through the use of large spans. Among the various classes of racing sailplanes, however, only the Open Class allows unlimited span, while all of the other FAI (Fédération Aéronautique Internationale) classes, Club, Standard, 15m Racing,

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and 18m Classes, have a maximum allowable value. The inter-thermal cruise, on the other hand, corresponds to flight at high speeds and low lift coefficients such that the reduction of profile drag dominates the design process. This trade-off between climbing and cruising is complicated further in that the optimum cruising speeds vary with the soaring conditions and depend on the achieved climb rate in thermals. Typically, the optimum cruising speed, called the MacCready speed-to-fly, is determined for a given sailplane and weather conditions using an idealized climb/glide cycle.[2] It is found that in weak weather, in which it is more difficult to regain altitude lost during cruise, the optimum cruising speed is not too much faster than that corresponding to the minimum glide angle (maximum lift-to-drag ratio) of the glider. In strong weather, the ability to achieve high climb rates dictates much faster optimum cruising speeds.

Because of the requirement to cruise at speeds much greater than that of the maximum lift-to-drag ratio, it is just as important that a modern sailplane have a reasonably flat speed polar, in which the sink rate does not increase too fast with speed, as it is that the glider have a high lift-to-drag ratio. In order to gain somewhat greater flexibility in the matching of the sailplane to soaring conditions on a particular day, most of the competition classes allow the use of disposable water ballast. In strong weather, the ballast is carried to increase the wing loading such that the speed polar shifts to higher airspeeds. The penalty in climb due to carrying additional weight is more than offset by having a higher lift-to-drag ratio at a given cruising speed. In weak weather, the ballast is not carried or can be dumped to regain the now needed better climbing ability. Similar gains are achieved with flaps, which are permitted in all of the FAI classes except Standard. In climbing flight, the flaps are lowered to achieve higher lift coefficients, while in cruise, they are deflected upward to shift the airfoil low-drag region to a lower lift-coefficient range. This upward deflection also reduces the nose-down pitching moment of the airfoil and thereby reduces trim drag.

The efforts at Penn State to develop winglets for high-performance sailplanes began in the early 1980's with a collaborative effort to design winglets for the 15m Class competition sailplanes of that era. Although work had already been done in this area, in practice it was found winglets provided little or no benefit to overall sailplane performance.[3-5] The widely held belief at that time, essentially the same as that held regarding winglets for transport-type aircraft, was that it was thought possible to help the climb portion of the mission profile, but not without overly penalizing the cruise performance. Thus, it was with some skepticism that efforts were taken to try to improve this situation.

The first task undertaken was a result of the observation that a winglet does not operate exactly as does a wing. For that reason, a winglet specific airfoil, the PSU 90-125, was designed. As not a great deal was known at this time about exactly how a sailplane winglet should operate, this was a conservative design that was intended to perform reasonably well over a wide range of operating conditions.

From this point, a trial and error process began 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 of limited value in the actual design process. Likewise, as the beneficial influence of a winglet is due to it favorably altering the flow field over the entire wing, meaningful wind-tunnel experiments require the use of a full-span model. Unless the wind tunnel has a very large test section, however, at the large aspect ratios typical of sailplanes, this would result in model chords that would likely operate at subcritical 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 would produce questionable results.[6] For these reasons, the parameters that were deemed the least important were set to what seemed to be reasonable values, while the values of the more critical ones were determined from flight test. Using some of the results from earlier work on winglets for transport and general aviation type aircraft,[7-9] along with simple calculations, the winglet height, planform shape, and cant (dihedral) angle, as defined in Fig. 1, were fixed. From this point, the goal was to establish the spanwise load distribution on the winglet that would interact in a reasonable way with the main wing and thereby produce an overall drag reduction. As the basic shape of this loading could be adjusted with twist or sweep, the twist was set, again being guided by the earlier work on winglets. In so doing, the geometry of the winglet blade was fixed. For minimum induced drag, if the planform is close to elliptical, then an elliptical load distribution requires that the spanwise lift coefficients be roughly constant. Thus, with the planform set, flight tests were undertaken in which woolen tufts were attached to the winglet and the load distribution adjusted using sweep until the stall pattern over the height of the winglet was uniform.

The last design parameter to be determined was the winglet toe angle. To establish this quantity, the idea employed was simply that there seemed to be little benefit in having the winglet being able to carry a load beyond that of the wing. This point was found by adding tufts to the main wing and adjusting the winglet toe angle until both wing and winglet stalled at roughly the same time.

Although it took a period of time and some contest successes before they began to be accepted, the result of the process was the first generally successful winglets that benefited overall cross-country performance over a wide range of thermal sizes and strengths.[10] In retrospect, with the understanding that has come since, it seems that this process, while systematic and logical, was accompanied with a certain amount of luck.

Even though the strategy employed resulted in a successful design, it was somewhat frustrating that the then available tools were not of much use in the development of these winglets. For this reason, a research program was undertaken in order to develop tools and a methodology for winglet design.[6, 11-14] These efforts began with the design of a new airfoil. Using the lessons learned and the improved understanding of how winglets operate, the PSU 94-097 airfoil was designed with much less conservatism than did its predecessor. In addition, theoretical tools were developed and validated with flight-test measurements. These methods are now quite reliable and the winglets designed using them generally meet their design goals without modification. Designs have been developed for a number of sailplanes. Those for the Schempp-Hirth Ventus 2, shown in Fig. 2, and the Schleicher ASW-27, detailed in Fig. 3, are typical of these designs and installations.

Technical Discussion

One of the consequences of producing lift on a finite wing is the generation of spanwise flow. In particular, the pressure gradients caused by the lower pressures on the upper surface relative to the higher pressures on the lower surface lead to inward spanwise flow on the upper surface and outward spanwise flow on the lower. At the trailing edge, the merging of these two flows having different directions generates the vorticity that is shed from a finite wing and is the origin of induced drag. 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, the endplate must be so large that the increase in wetted area drag far outweighs any drag reduction. A winglet, rather than being a simple fence which limits the spanwise flow, carries an aerodynamic load that produces a flow field that interacts with that of the main wing thereby reduces the amount of spanwise flow.[15] In essence, the winglet diffuses or spreads out the influence of the tip vortex such that the downwash and, in turn the induced drag, are 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.

Considered another way, the effect of the winglet is to produce a vertical diffusion of the vorticity in tip region. This diffusion process is also realized as an expansion of the wake in the far field due to induced velocities from the nonplanar components of the winglet. The out of plane bound vortex on an upward winglet induces horizontal velocities on the free wake that cause a spanwise spreading of the wake field. When referenced to the actual span, the resulting efficiency can be greater than that of an elliptical loading, emulating the effect of a span increase.[16] It should be noted that, while still beneficial, a winglet downward oriented would produce a contraction of the wake and is not as effective in reducing the induced drag as is a winglet oriented upward.

The profile drag contribution of the winglet is more straightforward than that of the induced drag. Any addition of wetted area will carry with it an increment in profile drag. Thus, adding winglets to aircraft causes an increase in wetted area and a corresponding increase in profile drag. The effect of the increased area is felt primarily at higher speeds, as the profile drag coefficient remains relatively constant while the drag increases with the square of the velocity. The additional wetted surface area penalty due to a winglet may be offset somewhat by removing some portion of the original wing tip when mounting the winglet. The large chords of the wing tip relative to the much smaller chords of the winglet provide a substantial compensation in wetted area, although the lower Reynolds number due to the smaller winglet chords will typically have somewhat larger profile drag coefficients. This cutting back of the tips is particularly effective in fixed-span classes. The total span is maintained at the maximum allowable by using a winglet dihedral angle of less than ninety degrees. In this way, a winglet may be added with less increase in wetted surface area than would occur if the tip of the existing planform were simply extended and turned upward.

It is also found that the amount of laminar flow over the outer portions of the main wing is increased by the presence of winglets.[17, 18] Without winglets, the transition line on the upper surface moves forward as the tip is approached, whereas the imposed favorable pressure gradient with winglets causes it to move aft. Consequently, to some extent, winglets offset their own increased wetted area penalty by decreasing profile drag over a part of the main wing.

Simply stated, the design goal of a winglet is to produce the most reduction in induced drag for the smallest increase in profile drag. The induced drag benefit of winglets is greatest at higher lift coefficients and lower flight velocities, while the profile drag penalty grows in magnitude as the lift coefficient decreases and the velocity increases. With the benefit and penalty being at different points in the flight regime, the optimization of the winglet geometry becomes complicated and ultimately requires an effective means of evaluating the changes in performance due to winglets over the entire flight envelope of the glider.

Winglet Geometry Issues

In the course of designing a winglet, a number of design variables must be considered. For fixing the geometry, the most important include determination of the airfoil section, chord distribution, height, twist, sweep, and toe angle. Because so many variables are involved, the design problem is difficult. It is further complicated by the operational profile of a sailplane, which combines a low-speed, high-lift coefficient climb phase with a high-speed, low-lift coefficient cruise phase, both of relatively equal importance.

Airfoil Considerations

As in most airfoil design efforts, the goal of the winglet airfoil design is to generate the lift required with the lowest possible drag. In the case of the winglet airfoil, the operational low-drag region for the winglet should correspond to that of the wing. Likewise, in low-speed flight the winglet should not stall before the main wing.

The relationship between the winglet lift coefficient and that of the main wing is unique for every wing/winglet combination, and ideally, every combination would have a specifically designed winglet airfoil. In most cases, however, such an effort is not warranted by the small gain in performance that would result. It should also be noted that the information needed to guide the airfoil design depends on the details of the winglet geometry, which in turn, is driven by the aerodynamic characteristics of the airfoil. Thus, the winglet/airfoil design process is iterative, and the result is the product of a number of design iterations. Consequently, in addition to the need for an accurate airfoil design method, the need is also clear for an accurate method of assessing the impact of winglet design details on the overall sailplane performance.

The attainment of the desired design goals for the winglet is made more difficult by the narrow chords and resulting low Reynolds numbers. This situation establishes a trade-off between trying to reduce the wetted area increase by using small chords against that of high profile drag coefficients due to the low Reynolds numbers. The small chords of the winglet dictate an airfoil that operates efficiently at Reynolds numbers in the range of 7.0×10^4 to 1.0×10^6. At such low values, laminar separation bubbles and the associated increases in profile drag are an important concern. Fortunately, this problem is helped somewhat in that the range of lift coefficients over which the winglet must operate is not as wide as that required for a typical wing. Thus, an airfoil designed specifically for a winglet can have somewhat lower drag than an airfoil designed for, say, a small unmanned air vehicle.

One important goal for the winglet airfoil design is to avoid poor section performance at low flight velocities. As the principle benefit of a winglet is in climb, stalling of the winglet in these conditions would certainly result in an overall loss in performance. Thus, the section must generate the maximum lift coefficients required by the winglet as the aircraft approaches stall. Likewise, low-drag performance over the entire operating range is important, but it must be considered in conjunction with the other constraints. As the profile drag increases with velocity squared, excessive section drag coefficients at low lift coefficients would severely impact aircraft performance at higher flight speeds. This consideration drives the lower lift coefficient portion of the airfoil drag polar. The degree to which these considerations influence the overall performance is again difficult to ascertain without considering the entire flight profile of the sailplane. The determination of the amount of gain needed at low-speed to offset a loss at high speed requires a relatively accurate method of performance evaluation.

Chord Distribution and Height

The most suitable winglet chord distribution is determined by a number of conflicting factors. Most important, the winglet must be able to generate the spanwise loading needed to produce the favorable interaction with the induced velocity field of the main wing. At low flight velocities, very small winglet chords can require lift coefficients greater than the airfoil can produce. This, of course, causes the winglet to be ineffective and can result in excessive drag due to the winglet stalling. Winglet chords that are too large, on the other hand, can also lead to poor performance in that high loading on the winglet can excessively load the tip region of the main wing and lower its planform efficiency. In extreme cases, this can cause the outboard sections of the main wing to stall prematurely. To avoid this situation, the winglet would have to be inefficiently under-loaded with the larger chords doing little but increasing the wetted area and the profile drag. This trade-off is further complicated by wanting small chords to minimize the added wetted area against not having chords so small as to result in high drag due to low Reynolds numbers. Although this depends on the airfoil under consideration, an appropriate airfoil can operate at quite low Reynolds numbers before the penalty due to an increased profile drag coefficient offset the drag reduction due to less area. This break-even point is, in fact, that at which halving the Reynolds number causes the profile drag coefficient to double. For most cases, the planform shape can be set without concern for the increased profile drag coefficient due to Reynolds number effects.

Although not so critical, once the basic chord dimension has been determined, the spanwise chord distribution should be such that the loading on the winglet is near elliptical and the induced drag on the winglet itself will be minimized. Once the chord distribution has been established, the winglet height is determined by the trade-off between the induced drag benefit and the wetted area penalty.

Twist, Sweep, and Toe Angle

After sizing the chord distribution and height by considering the required loading, profile drag and Reynolds number constraints, the winglet load distribution can be tailored further by spanwise twist and planform sweep. Increasing the sweep has the same effect on the load distribution as does adding wash-in along the winglet. Thus, the problem is simplified if one, say twist, is fixed and the sweep is tailored to achieve the best overall performance. The only concern to the designer is that too much sweep can introduce cross-flow instabilities that will cause the boundary layer to transition earlier than would otherwise be the case. Although there is not much information on this subject at the Reynolds numbers of interest here, it is known that the instability is reduced as the Reynolds number decreases. Consequently, as has been verified in wind-tunnel tests on winglet geometries, this should not be a problem provided that sweep angles are not in excess of, say, thirty-five or forty degrees.

After the planform has been determined, the toe angle at which the winglet should be mounted must be determined. This angle controls the overall loading on the winglet, as well as its overall effect on the load distribution of the main wing. Since the angle of attack of the winglet is a function of the lift coefficient of the wing, most likely the toe angle setting will only be truly optimal for one flight condition. Nevertheless, the determination of this angle to yield the best possible performance over the entire flight envelope is perhaps the most critical element of the design process.

The Winglet Design Process

Past Methodologies

Several approaches to winglet design have been utilized at Penn State.[6, 11-14] All of these methodologies have attempted to quantify, in one way or another, the tradeoff between the profile drag penalty and the induced drag benefit. Prior to the current approach, all other efforts made use of what has been termed the crossover point on the sailplane speed polar. This point corresponds to the airspeed at which the flight polar of the base aircraft and the aircraft with winglets intersect, or equivalently where the percent change in sink rate due to the winglets is zero. Below this speed, winglets are beneficial, while above this speed they are detrimental. Thus, the crossover point is the flight speed at which the benefit in induced drag due to winglets is equal to the profile drag penalty and occurs when

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

This simple expression indicates that the more the induced drag can be reduced for a given increase in profile drag, the higher will be the crossover point and the more effective the winglet.

After making a number of simplifying assumptions and expressing the total drag change due to the addition of a winglet in terms of the appropriate quantities, the derivative with respect to the winglet height can be set to zero and solved for the crossover velocity, $V_{CR,}$ to obtain

$$V_{CR} = \sqrt{\frac{const}{\rho \Delta h \sqrt{C_{Dp,WL}}}} \sqrt{\frac{W}{b}}$$

where the constant depends on how the winglet area increases and the overall induced drag decreases with winglet height, h. The lower the profile drag coefficient of the added winglet area, $C_{Dp,WL,}$, and the greater the span loading, the higher will be the velocity of the crossover point.

The understanding of the crossover point allows it to be controlled through the geometry of the winglet. In the early stages of using this simple idea, the crossover point was set to be higher than any anticipated cruising speeds for both the unballasted and ballasted cases. The use of this formula resulted in winglets that generally improved performance and, although based on a simple theory, was as good as the "not so good" ability to predict the changes in induced drag due to changes in winglet geometry.

As the ability to predict the induced drag for a given wing geometry improved,[11] the crossover point method was modified to take advantage of this. The expression equating the change in profile drag with the change in induced drag can be written more explicitly in terms of parameters describing the winglet geometry and the resulting aerodynamic influences as

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

where the terms having the "*WT*" subscript correspond to those for any area near the wingtip that is removed to mount the winglet, the subscript "1" to the original wing, and "2" to the one modified with the winglet. The weight of the sailplane, W, in this simple expression is considered to be unchanged by the wingtip modification. For fixed span classes, of course,

$b_1 = b_2$. If allowed, however, it is desirable to increase the span up to the point at which it hurts the profile drag more than it helps the induced drag. Thus, the problem for the winglet designer is to minimize the first term of this equation, the profile drag increase, while maximizing the other two, the drag area removed and the induced drag reduction. The induced drag factor, K_2, should be made as small as possible. Likewise, the net area increase should be minimized, as should the profile drag coefficient of any added area. While this expression does not capture the details of winglet design, it does capture the essence of the task.

Using either the closed form relation presented earlier, or some computational method of predicting the aircraft speed polars, the crossover velocity is adjusted, primarily using the toe angle and twist distribution, to allow the winglet to benefit performance over some part of the operational flight speed range. Shifting the crossover speed not only affects the speed range over which a benefit is achieved, but it also effects the magnitude of that benefit across the chosen range. Shifting the crossover to higher velocities reduces the performance gains due to the winglet at lower speeds, while shifting the crossover to lower velocities 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 these methods, and while based on simple ideas, they helped to establish the following rules of thumb. 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,[19, 20] experience has shown that pushing too far toward this optimum penalizes the profile drag far more than can be offset by the resulting induced drag reduction.[14] The design goal is clearly 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 main wing and the winglet. This would require that the chords at this point be the same, or that the lift coefficient at the root of the winglet be proportionally greater than that of the wingtip. Either way, the profile drag is considerably greater than that achieved with current designs. Up to now, it has been found that most of the potential induced drag benefit is achieved by designing or modifying the wing planform to be non-planar. Once this is done, the efforts of the designer are most rewarded by working toward minimizing the profile drag.

Present Design Approach

The broad nature of the sailplane mission profile greatly complicates the choice of an optimum crossover speed. In weak conditions, gains at low velocities in climb will offset a loss in cruise performance. Conversely, in strong conditions, not penalizing the high-speed cruise will be the most important to overall cross-country performance. While it is an effective method of predicting the change in aircraft performance due to the addition of winglets, and it does ensure some benefit, the use of the crossover point idea generally will not produce the best design. An 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 sailplane performance has been developed and combined with a thermal model, allowing the calculation of MacCready average cross-country speeds for specific weather conditions and aircraft configurations.[13, 14] The average speed is then used 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.

While MacCready theory is often used to assess overall performance, these efforts generally lack the ability to accurately and rapidly account for small changes in an aircraft configuration. The simplifications typically used, such as parabolic flight polars and approximated airfoil characteristics, introduce errors that are on the same order as the changes brought on by winglets. While useful for exploring trends and the basic characteristics of winglets, these methods are generally not accurate enough for design.

Prediction of Sailplane Performance

The calculation of sailplane performance forms the major component of the winglet design problem. As already stated, the performance evaluation must have sufficient resolution to discern the effect of winglets. As these effects are relatively small, errors or inconsistencies in other portions of the calculation may overshadow them. The accuracy necessary for successfully undertaking design activities such as winglets is obtained through the use of a performance program that has been developed to predict the straight and turning flight polars of sailplanes.[13, 14] To achieve the accuracy required, this program accounts for the effects of airfoil selection, trim drag, static margin, fuselage drag, flap geometry, and flap deflection scheduling. The most important element of the method is the analysis of the wing planform aerodynamics.

Essential to the accuracy of the analysis method is the interpolation of two-dimensional 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. In addition to the requirement of having accurate profile drag data, this necessitates interpolation of 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. As 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 multi-lifting line method and a three-dimensional lifting-surface panel code. The multi-lifting line method used here, which has been integrated directly into the performance program, divides the several chordwise lifting lines into segments, each segment having a parabolic distribution of vorticity.[3] 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 much less computational effort than required by a three-dimensional panel method. Although not accounting for the consequences of thickness and a free wake, as the panel method used here is able to do, the multi-lifting line procedure is able to quantify the effects of winglets. For initial design iterations, the increased speed of the multi-lifting line method more than offsets the small loss in accuracy.

The use of the multi-lifting line program and the interpolation of airfoil characteristics allow the performance program to produce accurate straight and turning flight polars for any aircraft configuration. The predicted performance for an unflapped sailplane, the Discus, is presented along with flight-test data[21] in Fig. 4. The predicted performance compares very well with the measured results. A similar comparison for a flapped sailplane, the ASW-22B, is presented in Fig. 5. The agreement for the individual flap settings is generally good, although there is some disagreement for the high-speed, negative flap deflections. At high speeds, however, small measurement errors have a large effect, and the differences between the predicted and measured points are not as large as the scatter between some of the measured points. Similar comparisons over a wide range of sailplane types have demonstrated that the method is able to resolve small enough differences between configurations to be of value in the winglet design effort.

For the final detailed design of the winglet, use is made of a panel method program that takes free-wake effects into account.[11] For the calculation of induced drag, this program makes use of the Kutta-Joukowsky theorem in the near field.[22] This eliminates some of the problems associated with attempting to account for wake relaxation in the far field using a Trefftz plane analysis. While the differences in results between a relaxed wake and a fixed wake analysis are generally small, these differences can be significant in determining the final winglet toe and twist angles.[6]

Analysis of Cross-Country Performance

With straight and turning flight polars available, analysis of crossover speeds is possible, but as mentioned previously, a more rigorous means of evaluating designs is desirable. This task is accomplished by 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.[13, 14]

The thermal model used in this analysis has a distribution of lift that varies parabolically with thermal radius. Thus, the thermal profile is defined by the strength of the lift at the core and the radius. Clearly, the thermal profile has a significant impact on the cross-country performance of a sailplane, and the most useful performance index would be the result of some particular mix of thermal strengths and profiles.[1] Nevertheless, the use of a single, representative thermal profile, as is done here, greatly simplifies the interpretation of the results while still yielding a meaningful comparison between different sailplane configurations.

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 climbing 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 Restricted Span Design Example

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. 6. Although gains are demonstrated, they are difficult to assess in the figures shown. Thus, the data are replotted in terms of lift-to-drag ratio verses velocity in Fig. 7. In addition to demonstrating the gains in carrying water ballast at higher cruising speeds, the winglets are seen to increase the lift-to-drag ratio over a significant portion of the operating range. To get an even better idea of the gains in lift-to-drag ratio, these data are again replotted in terms of the percentage increase in lift-to-drag ratio relative the same sailplane without winglets. These results are presented in Fig. 8. It should be noted that this winglet is such that the crossover points occur at airspeeds that are above the maximum allowable. While not true for all gliders, in this case there are no flight conditions for which the winglets penalize performance. While the percentage gain in lift-to-drag ratio does not appear to be very great, it is important that it is achieved without any penalty at higher speeds.

As has been noted, although the gain in lift-to-drag ratio is of interest, the true measure of the benefit of winglets is reflected in how they influence the overall cross-country performance. To demonstrate this, the percentage change in average cross-country speed relative to that of the baseline aircraft, without ballast and without winglets, is presented in Fig. 9. The winglets improve the cross-country performance for all the thermals considered, that is, for thermals having a 500 ft. radius and strengths, averaged across the diameter, of up to 10 kts. As expected, the performance gains are 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 decrease; however, for this glider, winglets are always a benefit to cross-country speed, even for average thermal strengths of 10.0 kts. and above. 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 about 8 kts, which corresponds to a predicted climb rate of about 5.2 kts. with full ballast. As indicated, ballast causes a reduction in average cross-country speed for average thermal strengths of less than 8 kts. For thermal strengths greater than this, winglets improve the cross-country speed, but only by a half-percent or so. In addition, the glider with winglets can carry ballast to slightly weaker conditions without penalty than can the glider without winglets.

An Unrestricted Span Design Example

Based on results from some of the early work on minimizing induced drag, it has long been accepted that when wingspan is unrestricted, a pure span extension will generally result in a greater performance gain than can be achieved with winglets. When profile drag considerations are included in the analysis, however, this conclusion is not so clear. For example, the minimum induced drag depends on maximizing both the span and the span efficiency. Unfortunately, because it is harder to maintain an elliptical spanwise load distribution as the span increases, the span efficiency usually decreases with increasing span. For wings of lower aspect ratios, the benefit of increasing the span generally far outweighs the penalty due to decreased span efficiency; however, for wings having very high aspect ratios, the benefit of increasing span is less assured. Because the lift distribution of a very high aspect ratio wing can be so far from elliptical, the increase in span efficiency due to properly designed winglet can yield a greater reduction in induced drag than does a comparable span increase. In addition, by reducing the spanwise flow at the wingtip, the winglet allows the tip region to operate better at high lift coefficients. This can result in improved turning performance and handling qualities.

For a span extension to achieve the best result, it is important that the chord distribution be continuous at the junction between the wing and the extension. Otherwise, the abrupt change in the loading that would result causes a significant penalty in induced drag. Such a discontinuity between the wing and a winglet, on the other hand, is not a problem. For the same increase in load perimeter (spar length), the winglet can have significantly less area and thereby a lower increase in profile drag than does a span extension.

To demonstrate the benefit of winglets on an unrestricted-span sailplane, the percentage increase in average cross-country speed for an ASW-22B due to pure span extensions compared to that due to a partial span extension plus a winglet is presented in Fig. 10. In this case, the area increases and the load perimeters for both are comparable. In fact, in spite of having less span, the extensions with winglets using less area but a slightly longer load perimeter, demonstrate a small but definite performance advantage over the glider with pure span extensions. This example also indicates that work remains to be done in finding the best tip treatment for unlimited span gliders, and that the potential exists for additional improvement.

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 is, in fact, one of the most difficult designs undertaken thus far. As an example of how critical these designs can be, the effect of the winglet toe angles on the Discus 2 winglet is presented in Fig. 11. As shown, even a small deviation from the optimum can cause the winglet to hurt performance. Furthermore, as many of these parameters are unique to each type of glider, each must have winglets tailored specifically for it. Generalities regarding winglet geometries can be disastrous. In the course of this work on winglets, one thing has become clear; it is much easier to make a glider worse with winglets than it is to make it better!

In some winglet design cases, it has been found that the winglets fix some problem of 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 optimum 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.

It has been found from experience and flight test that winglets often result in unanticipated performance gains and improved handling qualities. In particular, it has been found that winglets improve the flow in the tip region and thereby improve the effectiveness of the ailerons. 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 higher roll rates. Woolen tufts attached to glider wings have shown that much of the flow over the inboard tip during turning flight is separated, and this is nearly eliminated by the presence of a properly designed winglet. In addition to the resulting reduction in drag, this benefits safety in that the aileron effectiveness is retained much deeper into the stalled region 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, for the U.S. Open Class Nationals in 1999, just 68 points separated the first six places. As the winner had 4882 points, the difference between first and sixth places amounted to less than 1.5%. This is far less than the performance gains that have been achieved using winglets.

Since their shaky introduction a number of years ago, the notion that winglets can produce performance advantages is now widely accepted. At the World Championships in 1991, out of 105 competing gliders, only 19 used winglets. In the Championships of 1998, essentially every glider had winglets or some type of tip treatment. 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 airspeeds at which the glider operates, then there is no reason whatsoever not to take advantage of the benefits that winglets offer to both performance and handling qualities.

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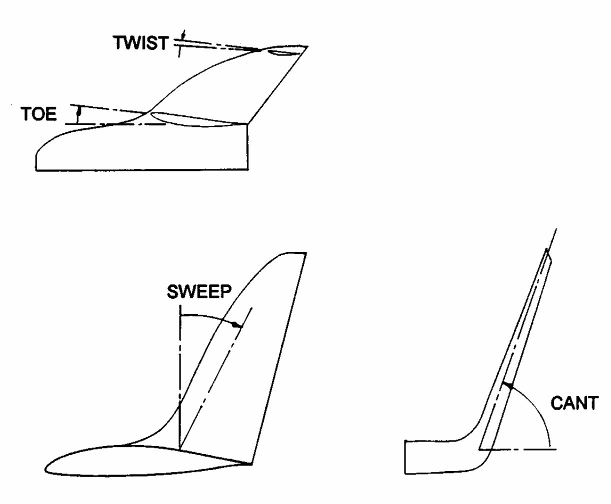

Fig. 1 Geometric quantities used to define winglet.

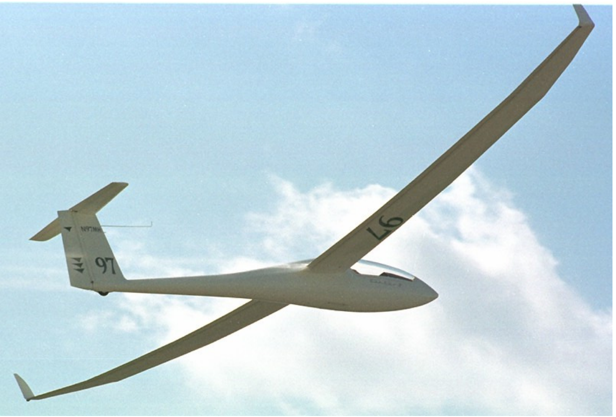

Fig. 2 Schempp-Hirth Ventus 2 sailplane with winglets.

Fig. 3 Detail of winglet on a Schleicher AS-W 27 sailplane.

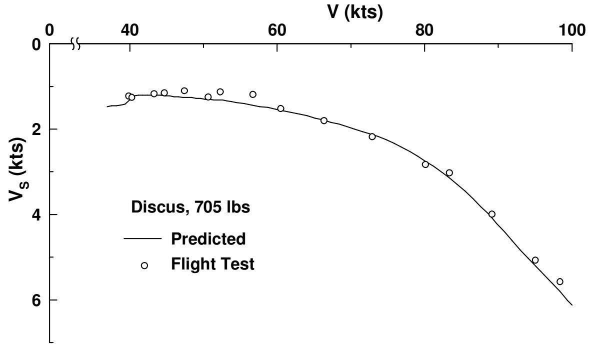

Fig. 4 Comparison of predicted and flight-test results for the straight-flight speed polar of the Schempp-Hirth Discus.

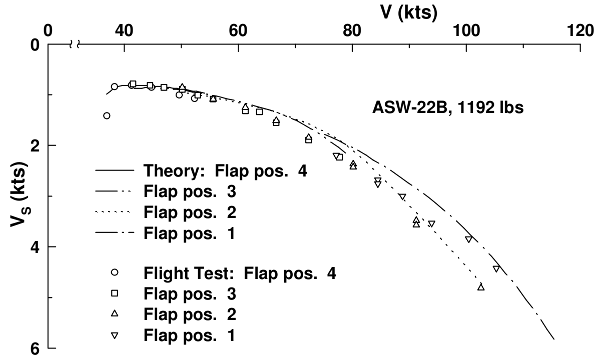

Fig. 5 Comparison of the predicted and flight-test results for the straight-flight speed polar of the Schleicher ASW-22B.

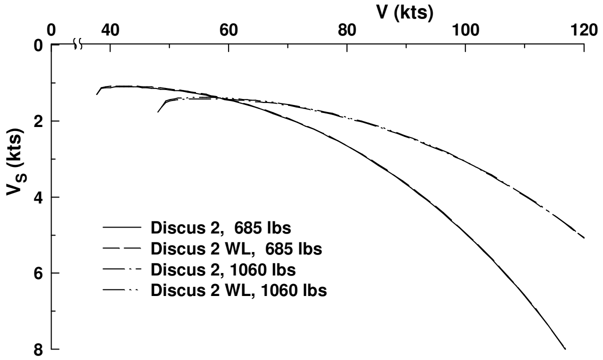

Fig. 6 Predicted straight flight polars of unballasted and ballasted Discus 2, with and without winglets.

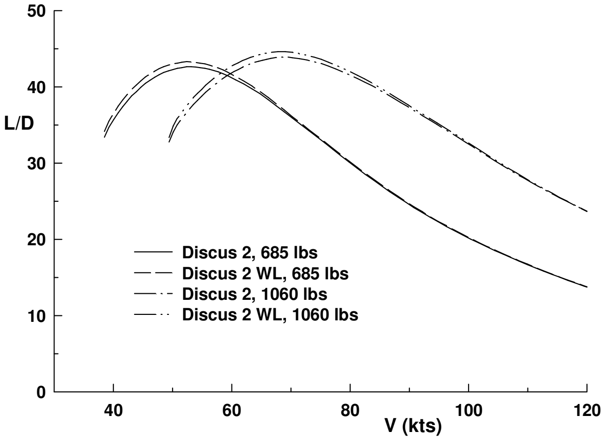

Fig. 7 Comparison of predicted lift-to-drag ratios for unballasted and ballasted Discus 2, with and without winglets.

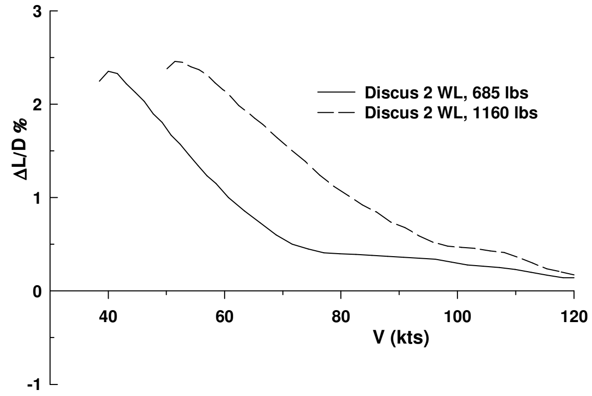

Fig. 8 Percentage gain in predicted lift-to-drag ratios due to winglets for unballasted and ballasted Discus 2.

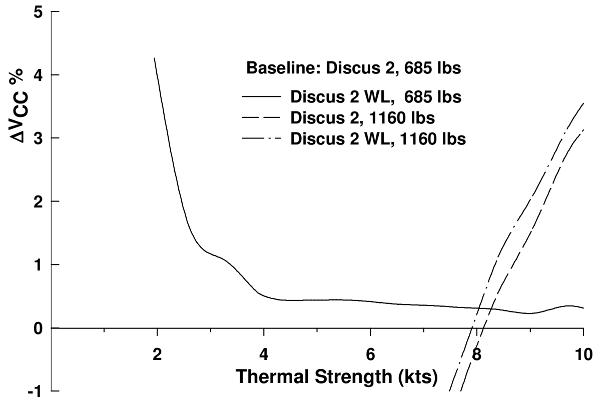

Fig. 9 Percentage gain in predicted average cross-country speed due to winglets and ballast relative to unballasted Discus 2 without winglets.

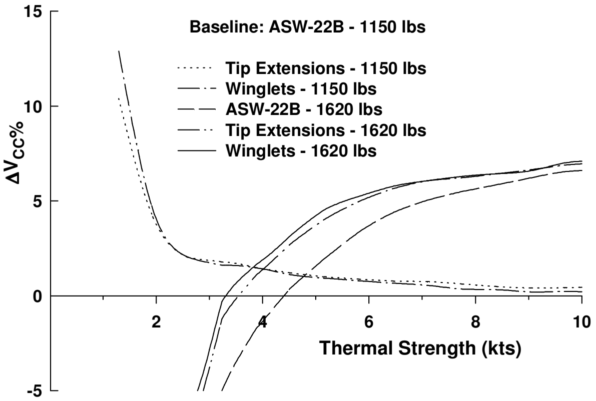

Fig. 10 Percentage gain in predicted average cross-country-speed due to tip extensions and winglets relative to an unballasted ASW-22 without winglets.

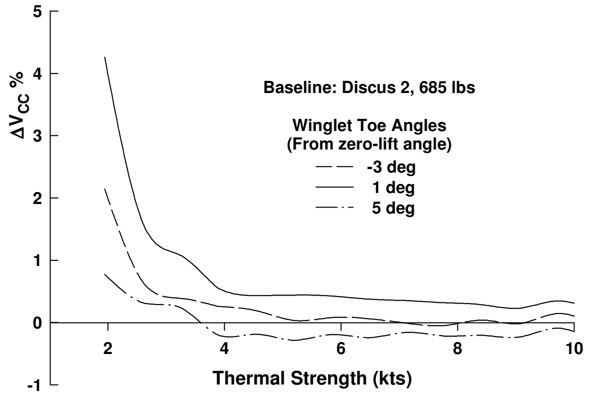

Fig. 11 Percentage change in predicted average cross-country speed as it depends on winglet toe angle for an unballasted Discus 2.