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Design of Winglets for High-Performance Sailplanes

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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. As understanding was gained, improved methods for winglet design were developed. 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. The predicted performance is in good agreement with flight-test results. The straight- and turning-flight speed polars are then used to obtain average cross-country speeds because they depend on thermal strength, size, and shape, which are used to design the winglets that provide the greatest gain in overall performance. Flight-test measurements and competition results have demonstrated that the design methods produce winglets that provide an important performance advantage over much of the operating range for both span-limited and span-unlimited high-performance sailplanes.

Nomenclature

b	=	span
C_{Dp}	=	profile drag coefficient averaged over span
c	=	wing chord
c_l	=	section lift coefficient
h	=	winglet height
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

FROM initially being able to do little to improve overall sailplane performance, winglets have developed to such an extent over the past 10 years that few sailplanes 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.

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 actually quite challenging.[1] This is largely because a successful design must balance, over a broad range of soaring conditions, the conflicting requirements of climbing well in thermals against cruising at high speeds between them.

For efficient climbing, a sailplane must circle and maneuver with a low sink rate in thermals that can change dramatically in strength, size, and shape from day to day and even over the duration of a single flight. Because this requires turning flight at low speeds and high lift coefficients, the reduction of induced drag is a major consideration in the design process. Although it can penalize the efficiency in cruising flight, the most straightforward method of reducing induced drag is to increase span. Among the various Fédération Aéronautique Internationale (FAI) classes of racing sailplanes, however, only the Open Class allows unlimited span, whereas all others, World, Club, Standard, Racing, and 18-M, have spans that are restricted by class rules.

In contrast to climb, interthermal cruise requires flight at high speeds and low lift coefficients such that the reduction of profile drag dominates the design process. This tradeoff 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 (see Ref. 2). In weak weather, in which it is more time consuming to regain altitude lost during cruise, the optimum cruising speed is only slightly faster than that corresponding to the maximum lift-to-drag ratio of the sailplane. In strong weather, the high climb rates dictate much faster cruising speeds.

Because of the requirement to cruise at speeds much greater than that for the maximum lift-to-drag ratio, it is even more important that a modern sailplane have a speed polar in which the sink rate does not increase too rapidly with increasing speed. To provide greater flexibility in matching the sailplane performance to varying soaring conditions, most competition classes allow the use of disposable water ballast. In strong weather, ballast is carried to increase the wing loading so that the speed polar shifts to higher airspeeds. The penalty in climb due to carrying additional weight is more than offset by the higher lift-to-drag ratio at a given cruising speed. In weak weather, ballast is not carried or can be dumped to regain better climbing ability. Gains are also achieved with flaps, which are permitted in several of the FAI racing classes. In climbing flight, the flaps are lowered to achieve higher lift coefficients, whereas in cruise they are deflected upward to shift the low-drag range of the airfoil to lower lift coefficients, as well as to reduce the nose-down

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pitching moment of the airfoil and, consequently, the aircraft trim drag.

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 with different spanwise directions generates the vorticity that is shed from a finite wing and is the origin of induced drag. Whereas the downwash created by the trailing-vortex system is necessary for the generation of lift, minimizing the spanwise flow minimizes the 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 drag due to the increased wetted area far outweighs any induced drag reduction. A winglet, unlike a simple fence that merely restricts the spanwise flow around the tip, uses an aerodynamic load to produce a flowfield that interacts with that of the main wing to reduce the amount of spanwise flow and, therefore, the induced drag.[3] In this way, the winglet accomplishes the same result as an endplate, but does so with less wetted area.

Thus, the goal of a winglet is to produce the most reduction in induced drag for the least increase in profile drag. For a sailplane, the induced drag benefit of winglets is greatest in climbing flight at low flight speeds, whereas the profile drag penalty is of importance in high-speed cruise. With the benefit and penalty occurring at different speeds, the optimization of the winglet geometry becomes complicated and ultimately requires an effective evaluation the changes in performance due to winglets over the entire flight regime of the sailplane.

Winglet Geometry

In the course of designing a winglet, a number of design variables must be considered. To fix the geometry, the most important features are the airfoil, chord distribution, height, twist, sweep, cant, and toe angle, as defined in Fig. 1.

Airfoil Considerations

As in most airfoil applications, the goal of a winglet airfoil is to generate the lift required with the lowest possible drag. Because the principal benefit of a winglet is in climb, stalling of the winglet under these condition results in an overall loss in performance. Thus, the airfoil 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. Because the profile drag increases with velocity squared, excessive section drag coefficients at low lift coefficients strongly affect aircraft performance at higher flight speeds. This consideration drives the lower lift coefficient portion of the airfoil drag polar. Clearly, the extent to which these considerations must be balanced requires a detailed examination of the entire flight profile of the sailplane.

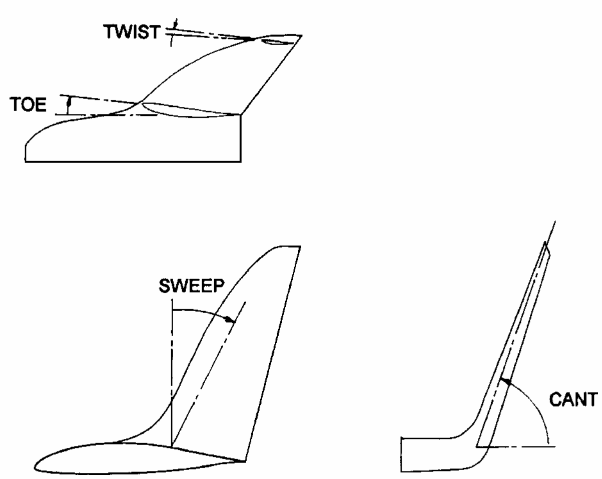

Fig. 1 Design variables used to define winglet geometry.

When an airfoil is considered for the winglet, it is clear that the winglet is unlike the wing in that its geometric angle of attack does not vary with airspeed but, rather, with yaw angle. Nevertheless, the winglet can be designed such that the induced velocities cause its lift coefficient to track very closely with that of the wing. An issue that was initially of some concern was whether even small yaw angles might cause the winglet airfoil to fall out of the low-drag range or possibly even stall. Thus, the airfoil that was used for the winglets initially, the PSU 90-125, was designed conservatively without sharp corners at the limits of the low-drag range such that any yawing would not be exacerbated by increased drag on the winglet. Because no such problems surfaced after several years of flight experience, the much less conservative PSU 94-097 airfoil was designed for higher performance by reducing the margins against unstable yawing behavior.

The design of an airfoil that accomplishes the desired goals is made difficult by the narrow chords of the winglet and the resulting low Reynolds numbers. This situation establishes a trade-off between restraining the wetted-area increase by using small chords and the high profile drag coefficients due to the low Reynolds numbers. In general, the chords of the winglet dictate an airfoil that operates efficiently at Reynolds numbers in the range from 7.0×10^4 to 1.0×10^6. At these Reynolds numbers, laminar separation bubbles and the attendant increases in profile drag are important concerns. A more complete discussion of winglet airfoil requirements and the design process is detailed in Ref. 4.

Cant, Chord Distribution, and Height

The drag due to the additional wetted area of adding a winglet may be offset somewhat by removing a portion of the original wing tip when mounting it. Although the lower Reynolds numbers due to the small winglet chords will have higher profile drag coefficients, these are more than offset by the area reduction near the tips, which is particularly effective in the restricted-span classes. Provided that it does not result in a cant angle that is too small, the span is maintained at the maximum allowable by using a cant angle of less than 90 deg.

It should be noted that induced-drag predictions based on a planar wake indicate that a winglet oriented downward results in the same induced-drag reduction as one oriented upward. When a free-wake model is employed, while still beneficial, the downward-oriented winglet produces a spanwise contraction of the wake and is less effective in reducing the induced drag than an upward-oriented one.[5]

The most suitable winglet chord distribution is determined by a number of conflicting factors. Most important, the winglet must generate the spanwise loading needed to produce the favorable interaction with the induced-velocity field of the wing. At low flight speeds, very small winglet chords would require lift coefficients greater than the airfoil can produce. This, of course, causes the winglet to be ineffective and results 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 excessively loads the tip region of the wing and lowers its planform efficiency. In extreme cases, this can cause the outboard regions of the wing to stall prematurely. To avoid this situation, the winglet would have to be inefficiently underloaded with the larger chords doing little but increasing the wetted area and profile drag. An appropriate airfoil operates at quite low Reynolds numbers before the penalty of an increased profile drag coefficient offsets the drag reduction due to less area. This break-even point is 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 unfavorable 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 of the winglet itself is minimized. The winglet height is then determined by the tradeoff between the induced-drag benefit and the wetted-area penalty.

Twist, Sweep, and Toe Angle

After the chord distribution and height are sized, the winglet load distribution can be tailored further by spanwise twist and sweep. Increasing the sweep has the same effect on the load distribution as adding wash-in along the winglet. Thus, the problem is simplified if one variable, for example, twist, is fixed and the other, sweep, is tailored to achieve the best overall performance. For the designs considered thus far, the twist angle was set at 2.6 deg. One concern is that too much sweep can introduce crossflow instabilities that will cause the boundary layer to transition prematurely. Although there is little information on this subject at the Reynolds numbers of interest, 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 do not exceed 35 or 40 deg.

After the planform has been finalized, the toe angle must be determined. This angle controls the overall loading on the winglet, as well as the overall effect on the load distribution of the wing due to the winglets. Because the angle of attack of the winglet is a function of the lift coefficient of the wing, the toe angle is only truly optimal for one flight condition. At the cost of high-speed performance, the greater the toe angle is, the greater the benefit in climb. Thus, the determination of this angle to yield the best possible performance over the entire flight envelope is usually the most critical element of the design process.

Winglet Design Process

Early Trial- and-Error Approach

The efforts at Pennsylvania State University to develop winglets for high-performance sailplanes began in the early 1980s with a collaborative effort to design winglets for the 15-M 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.[6–8] The widely held belief at that time, essentially the same as that held for transport-type aircraft, was that although 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 improve this situation.

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 flowfield over the entire wing, meaningful wind-tunnel experiments require a full- or half-span model. Unless the wind tunnel has a very large test section, however, the high aspect ratios typical of sailplanes result in model chords that would produce excessively low Reynolds numbers. To address these problems, methods of simulating full-scale flowfields with truncated spans have been explored, but, in every case, the necessary compromises produced questionable results.[9] For these reasons, the parameters that were deemed the least important were set to reasonable values, whereas the more critical parameters were determined from flight test. With the use of some of the results from earlier work on winglets for transport and general aviation aircraft,[10–12] along with simple calculations, the winglet height, planform, and cant 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 could be adjusted with twist or sweep, the twist was set, again being guided by the earlier work on winglets. For minimum induced drag, if the planform is close to elliptical, the load distribution yields spanwise lift coefficients that are roughly constant. Thus, with the planform set, the load distribution was adjusted using sweep until the stall pattern on the winglet was uniform in the spanwise direction, as determined by flight tests using tufts.

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 tufts.

Although it took some time and racing 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.[13]

Even though this trial-and-error approach resulted in a successful design, it was clearly not optimal and left much to be desired. For this reason, a research program was undertaken to develop tools and a procedure for winglet design.[9,14–17]

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 percent change in sink rate due to the winglets is zero. 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, whereas above it 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, that is, when

$$\Delta D_{\text{profile}} + \Delta D_{\text{induced}} = 0$$

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

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

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

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 previously predicted results.[11] The lower the profile drag coefficient of the added winglet area, $C_{Dp,\text{WL}}$, and the greater is 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 dictated by 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,[14] 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 can be written more explicitly in terms of parameters describing the winglet geometry and the resulting aerodynamic influences as

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

where the term having the WT subscript corresponds to the area near the wing tip 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 sailplane, W, is considered to be unchanged by the wing tip 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 wing tip 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. Although this expression does not capture the details of winglet design, it does capture the essence of the task.

When either of the closed-form relations presented to guide the winglet design was used, a traditional drag buildup was performed to predict the sailplane speed polars. Then crossover speed was 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 although 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, whereas a great deal of work has been directed toward determining the optimum geometries for minimum induced drag,[14,18–20] experience has shown that pushing too far toward this optimum penalizes the profile drag far more than can be offset by the induced-drag reduction.[17] 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 wing tip. 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. In short, most of the induced-drag benefit is achieved by making the wing planform nonplanar. Once this is done, minimizing the profile drag of the winglet is paramount.

Present Design Approach

The broad nature of the sailplane 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. Whereas 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. 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 (see Refs. 16 and 17). 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. Although useful for exploring trends and the basic characteristics of winglets, these methods are not accurate enough for design.

Prediction of Sailplane Performance

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 are 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.[16,17] 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 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 provide such data accurately, 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 wing 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.[6] 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.

The use of the multiple lifting-line program and the interpolation of airfoil characteristics allows the performance program to produce accurate straight- and turning-flight polars for any aircraft configuration. The predicted performance of a Standard-Class sailplane (unflapped, 49.2-ft wingspan), the Discus, is presented along with flight-test data[21] in Fig. 2. The predicted performance compares very well with the measured results. A similar comparison for an Open-Class sailplane (flapped, 82.0-ft wingspan), the ASW 22B,

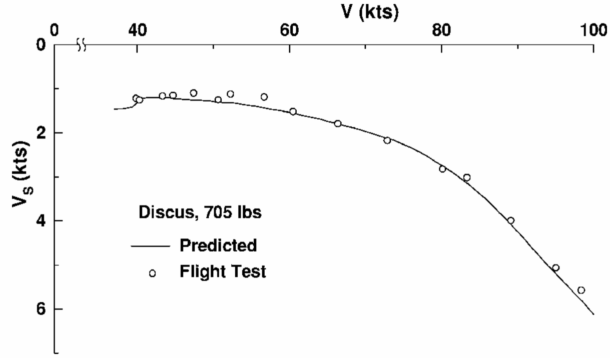

Fig. 2 Comparison of predicted and flight-test results for the straight-flight speed polar of the Schempp-Hirth Discus 1.

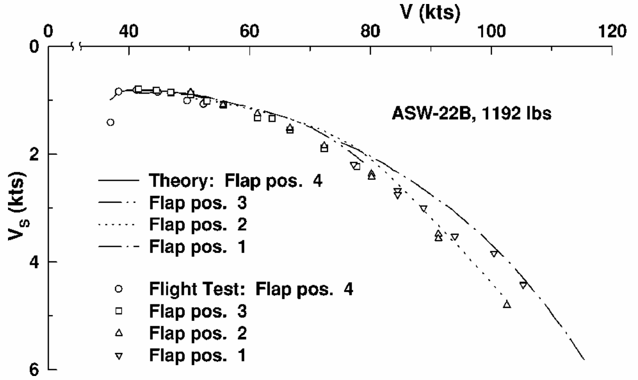

Fig. 3 Comparison of the predicted and flight-test results for the straight-flight speed polar of the Schleicher ASW 22B.

is presented in Fig. 3. 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, not only do small measurement errors have a large effect, but the differences between the predicted and measured points are less than 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.[14] For the calculation of induced drag, the program applies the Kutta–Joukowsky theorem in the near field (see Ref. 22). This eliminates some of the problems associated with attempting to account for wake relaxation in the far field using a Trefftz-plane approach. Although 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.[9]

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 rotational flowfield are neglected.

Analysis of Cross-Country Performance

With straight- and turning-flight polars available, analysis of crossover speeds is possible but, as already mentioned, 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 (see Refs. 16 and 17).

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.[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 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 interthermal 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.

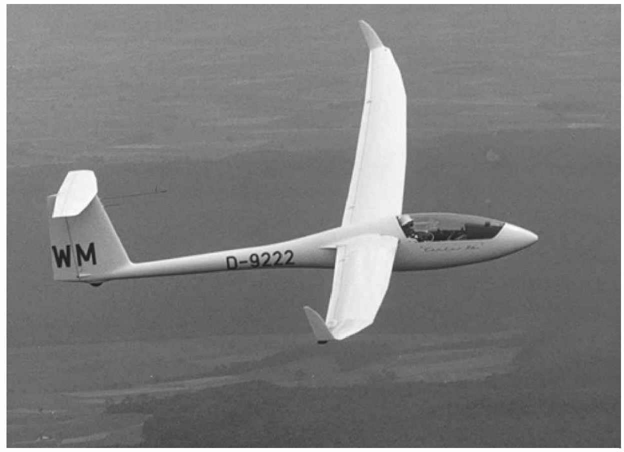

Fig. 4 Schempp-Hirth Ventus 2ax sailplane with winglets.

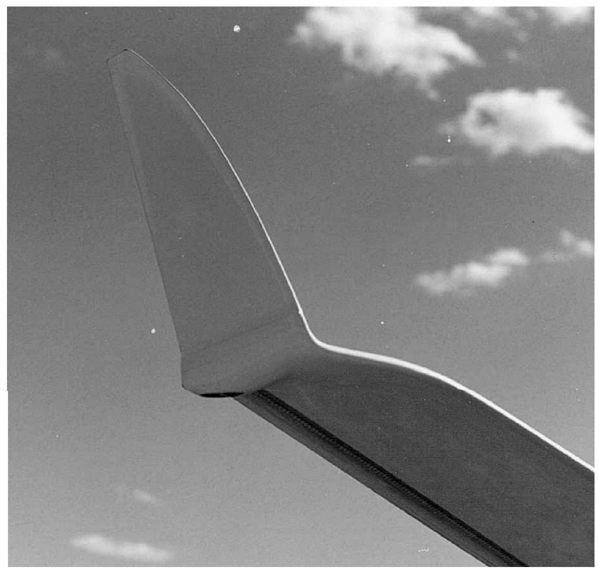

Fig. 5 Detail of winglet on a Schleicher ASW 27 sailplane.

The current design methodology has been developed and validated with flight-test measurements, comparison flying, and a long record of competition results. The 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. The winglets shown on the Schempp-Hirth Ventus 2, shown in Fig. 4, and on the Schleicher ASW 27, detailed in Fig. 5, are typical of these designs.

Gains in Cross-Country Performance

Restricted-Span Example

To appreciate 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. Because the gains are difficult to assess in this format, the data are replotted in terms of lift-to-drag ratio 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 better demonstrate the gains in lift-to-drag ratio, these data are again replotted in Fig. 8 in terms of the percentage increase in lift-to-drag ratio relative the same sailplane without winglets. Note that this winglet produces crossover points at airspeeds greater than the maximum allowable. Although not optimal, in that slightly faster average cross-country speeds are possible, racing tactics often require that pilots cruise at speeds faster than those dictated theoretically. In these cases, the

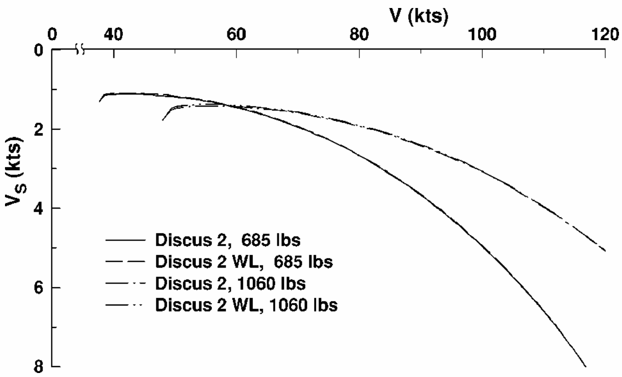

Fig. 6 Predicted straight-flight polars of unballasted and ballasted Discus 2, with and without winglets.

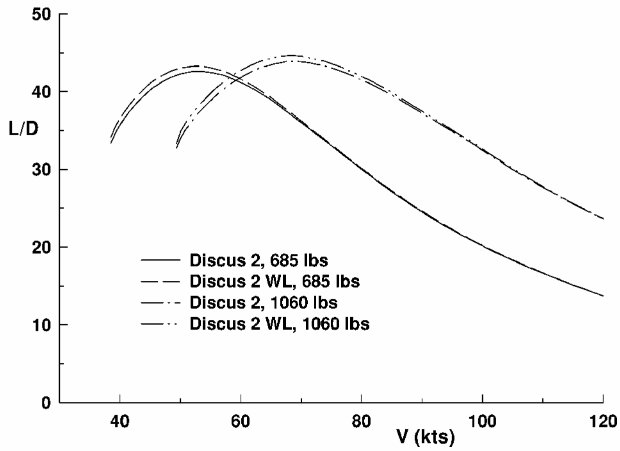

Fig. 7 Comparison of predicted lift-to-drag ratios for unballasted and ballasted Discus 2, with and without winglets.

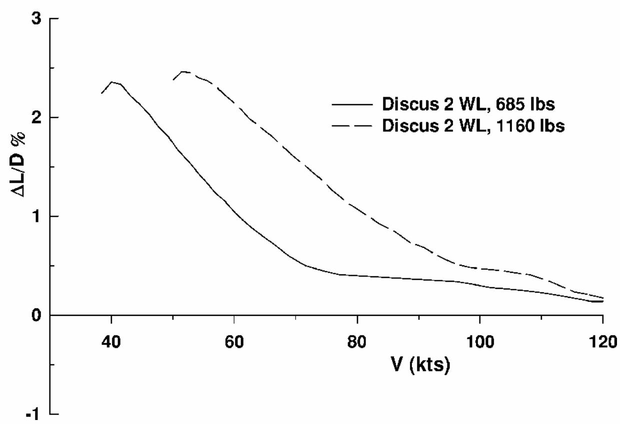

Fig. 8 Percentage gain in predicted lift-to-drag ratios due to winglets for unballasted and ballasted Discus 2.

drag penalty due to the winglet operating above the crossover point is severe. Although not done in earlier designs, the best overall winglets have been found to be those having a crossover point that is greater than any reasonable cruising speed, such that there are no flight conditions for which the winglets penalize performance. Whereas the gains at low inter thermal cruising speeds are less than possible, a benefit is now realized throughout the entire speed range.

Although the gain in lift-to-drag ratio is of interest, the true measure of the benefit of winglets is reflected in their influence on the overall cross-country performance. To consider this, the percentage change in average cross-country speed relative to that of the baseline

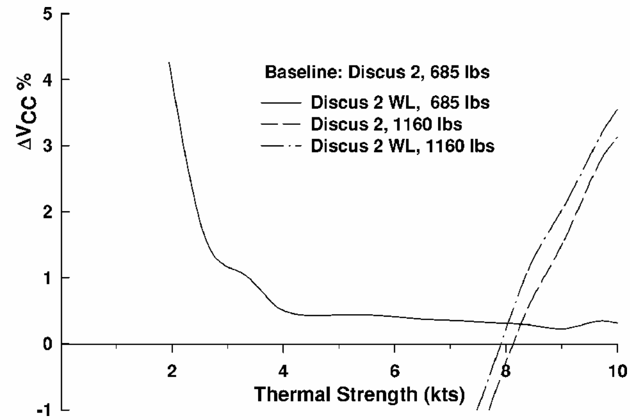

Fig. 9 Percentage gain in predicted average cross-country speed due to winglets and ballast relative to unballasted Discus 2 without winglets.

aircraft, without ballast and without winglets, is presented in Fig. 9. The winglets improve the cross-country performance for all of 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 because the winglets allow for some climb rate, whereas, without winglets, it is minimal or zero. With increased thermal strengths, the benefit due to winglets decreases; however, for this sailplane, the cross-country speed is never penalized, even for average thermal strengths of 10 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 fully ballasted climb rate of about 5.2 kts. For thermal strengths greater than this, winglets increase the cross-country speed, but only by about a $\frac{1}{2}$%. In addition, the sailplane with winglets can carry ballast at slightly weaker conditions without penalty than can the sailplane without winglets.

Unrestricted-Span Example

Based on 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. Unless the chord distribution is continuous between the main wing and the span extension, however, the abrupt change in the span loading will cause excessive shedding of vorticity into the wake and result in a significant induced-drag penalty. A discontinuity in the chord at the juncture of the wing and a winglet, on the other hand, does not result in such a gradient in the spanwise load distribution, and the induced drag is not penalized as severely. For the same increase in load perimeter (spar length), the winglet can have significantly less area, and thereby a lower profile drag increase, than does the span extension.

Even without considering profile drag, span extensions on very large span wings can yield less induced-drag benefit than might be expected. This is because the minimum-induced drag depends on maximizing both span and span efficiency. For wings of lower aspect ratio, the benefit of increasing span usually outweighs the penalty due to decreased span efficiency; however, as the aspect ratio increases, it becomes harder to maintain an elliptical spanwise load distribution, and therefore, the span efficiency decreases with increasing span. For wings having very high aspect ratios, the benefit of increasing span is less assured. Consequently, because the lift distribution of a very high aspect ratio wing can be so far from elliptical, the increase in span efficiency due to a 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 wing tip, the winglet allows the tip region to operate more efficiently at high lift coefficients, which can result in improved turning performance and handling qualities.

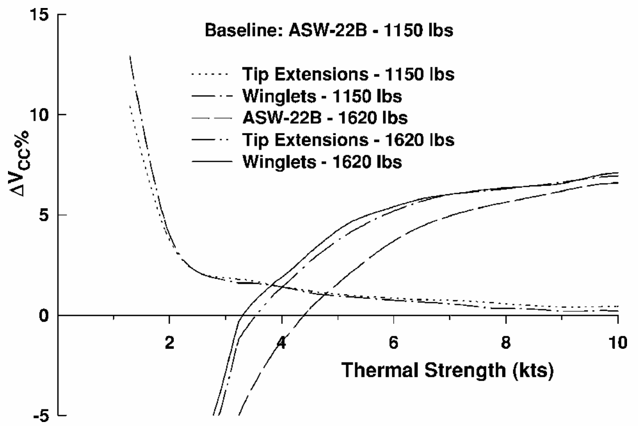

Fig. 10 Percentage gain in predicted average cross-country speed due to tip extensions and winglets relative to an unballasted ASW 22 without winglets.

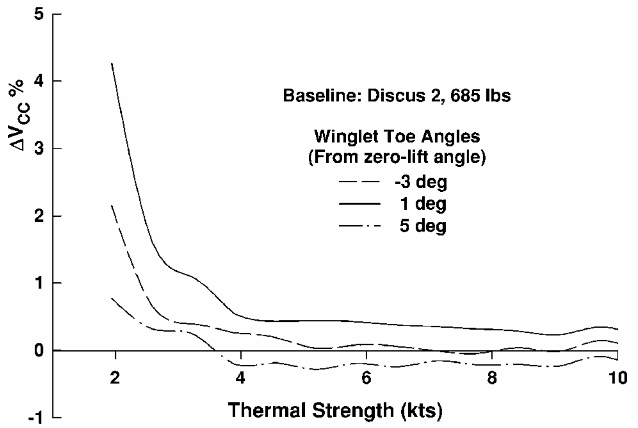

Fig. 11 Percentage change in predicted average cross-country speed as it depends on winglet toe angle for an unballasted Discus 2.

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 (86.6-ft total span) compared to that due to a partial span extension plus a winglet (85.1-ft total span) is presented in Fig. 10. In this case, the area increases and loading 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 sailplane with pure span extensions. This example also indicates that work remains to be done in finding the best tip treatment for unlimited-span sailplanes and that the potential exists for additional improvement.

Other Considerations

In designing winglets for a variety of sailplanes, as well as for a number of nonsailplanes, it appears that all wings can be improved with winglets, although the better the original wing is from an induced-drag standpoint, the smaller the possible gain is and the more difficult the design process is. The restricted-span case presented here is one of the most difficult designs undertaken thus far. As an example of how critical these design parameters can be, the effect of winglet toe angle on average cross-country speed is presented in Fig. 11, demonstrating that even a small deviation from the optimum can cause the winglet to hurt performance. Furthermore, because many of the parameters are unique to each type of sailplane or aircraft, each must have winglets tailored specifically for it. Generalities regarding winglet geometries, particularly optimum toe angle, are not possible. In the course of this work, one thing has become clear: it is much easier to make a sailplane worse with winglets than it is to make it better.

In some cases, it has been found that winglets fix some problem of the original wing. For example, in the case of a flapped sailplane, it is important that the ailerons/flaperons extend to the wing tip. Otherwise, when the flaps and ailerons are deflected upward for high-speed cruise, the tips are loaded more than they should be for optimum spanwise loading. Although only a small portion of the wing is influenced, a very significant induced-drag increase results. In these cases, cutting the tip back to the aileron to mount the winglet can result in gains, especially at high speeds, that would not be expected just by the addition of the winglets.

Based on experience and flight test, winglets usually result in unanticipated handling qualities improvements and, consequently, additional performance gains. In particular, 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 also allows higher roll rates. In addition, safety increases because aileron effectiveness is retained deeper into the stalled region.

Conclusions

Although the performance gains achieved with winglets are only a few percent at moderate thermal strengths, such small differences can be important in determining the outcome of many cross-country flights or contests. For example, at a recent U.S. Open-Class Championships, the first six places were separated by less than 1.5%. This is far less than the performance gains that can be achieved with winglets.

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 speeds at which the sailplane operates, there are no reasons to not take advantage of the benefits that winglets offer in both performance and handling qualities.

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