SAILPLANE WINGLET DESIGN

by Mark D. Maughmer and Peter J. Kunz

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SUMMARY

Although the accuracy of methods for the design and analysis of winglets has been limited, the performance gains achieved through their use are now well established. 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 discretized, 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. This information can then be used to obtain cross-country performance over a range of thermal strengths and profiles. The performance predictions agree well with flight-test results, and are consistent with the winglet design experiences obtained thus far. Example designs for the Schempp-Hirth Discus and the Schleicher ASW-20 demonstrate that winglets can provide a small but important performance advantage over much of the operating range for both Standard and Racing Class sailplanes.

INTRODUCTION

The increased acceptance of winglets within the soaring community, and a greater appreciation of the precision required for the design of effective winglets, has established the need for improved analysis and design techniques. To date, the most prevalent application of winglets has been in the span limited classes, that is, the Standard Class, Racing Class, and the new 18-Meter Class. In these arenas, winglets have provided increased performance at a moderate cost without violating the dictated span limit. An area of less implementation has been in the Open Class. With no span limitation, it has been generally accepted that pure span extensions offer a greater benefit than do winglets, although whether or not this is true is subject to some debate. In depth studies of this and similar applications have been hampered the lack of suitable analysis tools.

The development of methods for the design and analysis of winglets has been the focus of a research effort that has been on-going at Penn State University for a number of years.[1-4] Over the course of this effort, winglet performance has been gradually improved, currently providing gains as high as ten percent in both sink rate and glide ratio. While significant, improved design methodologies offer the possibility of even greater gains. Recent work has centered on a method to evaluate the average cross-country speed based on a detailed prediction of the sailplane performance, a thermal model, and MacCready Speed-to-Fly theory. Although these tools have been used in the past, their combination with an efficient and accurate representation of specific aircraft aerodynamics allows a wide range of geometries to be investigated in any particular design effort.

TECHNICAL DISCUSSION

Most basically, the design problem of adding winglets or span extensions to an existing sailplane can be stated as a trade-off between reducing the vortex induced drag against the penalty of additional profile drag. The crossover point of this trade-off is represented by the equation

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

which can be written as

$$(1/2)\rho V^2 [S_{WL} C_{DPWL} - S_W C_{DPW}] = (2W^2/\pi\rho V^2)[K_2/b_2^2 - K_1/b_1^2]$$

where S_{WL} is the planform area added by the winglet or span extension, and S_w is the wing area that might be removed by the winglet installation. C_{DPWL} is the profile drag coefficient averaged over the span of the winglet or span extension, and C_{DPW} is that averaged over any area removed. K_2 and K_1, are, respectively, the induced drag factors of the new wing and that of the original one ($K = 1.0$ corresponding to an elliptical lift distribution), while b_2 and b_1, are the projected spans of the new and the original wings, respectively. As is usual, ρ is the air density, V is the airspeed, and W is the weight of the sailplane (which in this simplified expression is considered to be unchanged by the wingtip modification). Thus, the problem for the winglet designer is to maximize the right side of this equation while minimizing the left. It is desirable to increase the span, if allowed, and minimize the induced drag factors as much 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 include all of the details of winglet design, it does capture the essence of the task.

In the course of working on winglet design, several important guidelines have evolved. First, the induced drag factor can be reduced significantly by nonplanar geometries; however, the optimum geometry for minimum induced drag typically costs far too much in profile drag to result in an overall gain.[1, 5] It is found that much of the possible induced drag reduction can be achieved by a less-than-optimum, from the induced drag standpoint, out-of-plane geometry. Beyond this point, the effort should concentrate on reducing the profile drag for the given reduction in induced 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 fairly complicated and requires an effective means of evaluating the changes in performance due to winglets over the entire flight envelope of the glider.

A substantial amount of work has been undertaken by a number of researchers to understand the aerodynamics of winglets and how they can be best implemented.[6-10] The full extent of these studies will not be repeated here, but a brief overview will be presented.

Induced Drag Contribution

Properly implemented, winglets result in an increase in planform efficiency that yields a reduction in the induced drag of the wing. This benefit in induced drag is primarily realized at higher lift coefficients and the corresponding lower flight velocities. The reasons for this improvement can be explained in a number of ways.

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. It is this spanwise flow that produces the vorticity shed from the trailing edge of a finite wing that is the origin of induced drag. It has been known for nearly a century that an endplate at the tip of a finite wing can help to reduce spanwise flow and yield a reduction in induced drag. As was found experimentally during the 1970's, the effectiveness of such an endplate improves significantly if it is configured in such a way as to produce an inward sideforce that allows its own induced velocity field to partially cancel that of the main wing, thereby reducing the amount of spanwise flow.[6, 7] Most simply, the effect of these specifically configured tip devices, called winglets, is to produce a vertical diffusion of the vorticity in the vicinity of the wing tip. This "spreading out" of the tip vorticity is present in the wingletoff/winglet-on wake comparison depicted in Figure 1.

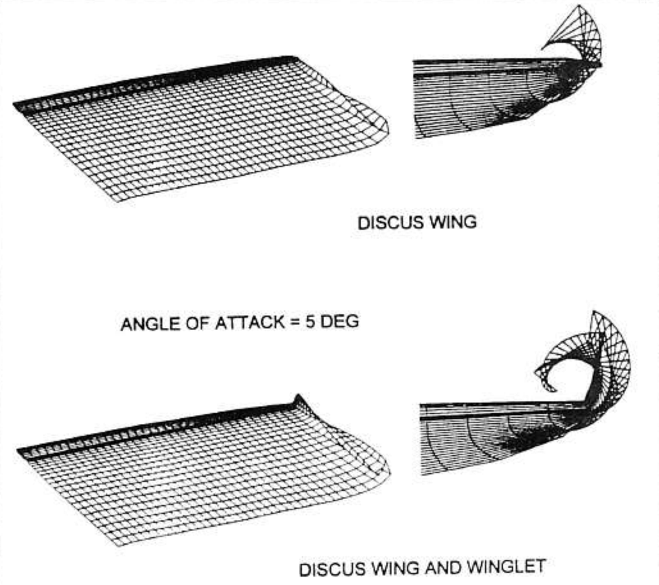

Figure 1. Rear view of Schempp-Hirth Discus wing and wake with and without winglet. Generated using the PMFW program.[1-3]

The displacement of the wing tip out and away from the main wing planform reduces the effect of the shed vorticity on the wing by displacing the concentrated vorticity away from the wing. In this manner, the winglet directly emulates the effect of a planar span extension and an increase in the length of the load perimeter. This can be observed in both the near-field and far-field wakes shown in Figure 1.

The 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. This also emulates the effect of a span increase, visible in the far-field, full-span comparison shown in Figure 1. It should be noted that a winglet oriented downward would produce a contraction of the wake and, consequently, is not as effective in reducing the induced drag as is a winglet oriented upward.

Another benefit of winglets, which is not achieved by a simple span extension, is the effect on the spanwise lift distribution, particularly in the region of the wing tip. As depicted in Figure 2, the influence of the winglet effectively loads the planform in the tip region, increasing the local lift coefficients and filling out the spanwise lift distribution. Planform efficiencies greater than those of an elliptical wing are possible. This occurs because, as evidenced by the extension of the roughly constant lift coefficients to beyond the actual tip location, the tip loaded spanwise lift distribution is, in fact, behaving like that of a nearly elliptically loaded planform of a greater span. When referenced to the actual span, the resulting efficiency is greater than that of an elliptical loading.

Profile Drag Contribution

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 detrimental effect of the additional wetted surface area of a winglet may be somewhat offset by removing a small portion of the 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 result in 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 these cases, a winglet may be added with less increase in wetted surface area than would occur if it were simply added vertically to the tip of the existing planform.

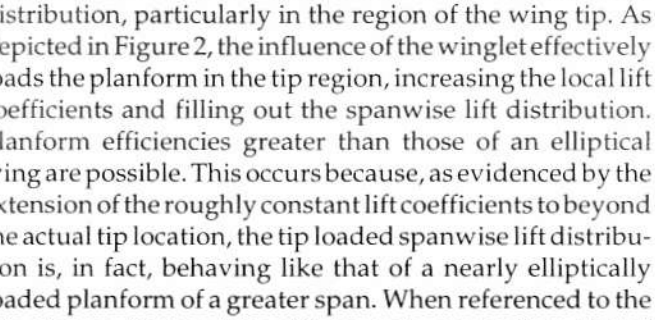

Figure 2. Spanwise variation in section lift coefficient of Discus with and without winglets. The spanwise location considers the winglet to be folded down in the plane of the main wing.

Although an improvement in the induced drag efficiency of the planform is also possible using span extensions with properly implemented chord and twist distributions,[10, 11] for span limited aircraft winglets are the only allowable approach. For span unlimited cases, however, the benefit of winglets as compared to span extensions is much less certain. In general, winglets achieve much of the reduction in induced drag that would span extensions, but often with less profile drag because of a smaller increase in wetted area. Given the choice of a span extension, winglets, or a combination thereof, it its possible that a winglet having an average chord that is small relative to that of the wing tip can achieve less total drag than an equivalent span extension. This trade-off is case specific and warrants additional study.

WINGLET GEOMETRY ISSUES

The winglet design problem is dominated by the determination of the airfoil section, the planform shape, and the twist and toe angles. Because so many variables are involved, however, 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. In any case, the design must consider the winglet airfoil, chord distribution, height, twist, sweep, and toe angle.

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. For a representative case, the required average winglet lift coefficient as it depends on the wing lift coefficient is presented in Figure 3. 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 sailplane/winglet combination. Ideally, every combination should 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 as

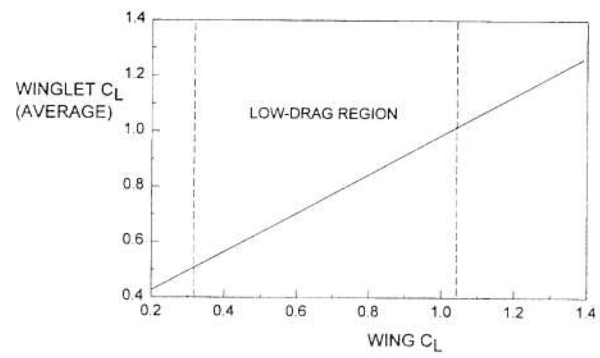

Figure 3. Comparison of the wing and winglet lift coefficients.

presented in Figure 3 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 shown is the product of a number of such iterations. Consequently, in addition to the need for an accurate airfoil design method, the need for an accurate method of assessing the impact of winglet design details on the overall sailplane performance is clearly demonstrated.

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 winglet wetted area with 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 1.0×10^5 to 1.0×10^6. At such low values, laminar separation bubbles and the associated increases in profile drag become very important. Fortunately, this problem is helped somewhat by the narrower than usual range of lift coefficients over which the winglet must operate. Thus, an airfoil designed specifically for a winglet can have lower drag than a low Reynolds number airfoil designed for, say, a radio-controlled model airplane.

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 allow for the maximum lift coeffcients required by the winglet as the aircraft approaches stall. Likewise, low-drag performance over the entire operating range is of importance, but 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 effect 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 effect the overall performance is again difficult to ascertain without considering the entire flight profile of the sailplane. How much of a gain at low-speed is needed to offset a loss at high speed and vice versa requires a relatively sophisticated method of performance evaluation.

Based on the required winglet operational lift coefficient and Reynolds number ranges, an airfoil has been designed which meets the winglet operating requirements with minimum profile drag.[12, 13] This is an iterative procedure in which the winglet operating points that are used to define the airfoil specifications are strongly influenced by the airfoil itself. The outcome of this design process is an airfoil having a thickness ratio of 9.7 percent, the theoretical aerodynamic characteristics of which are presented in Figure 4.

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 loading, cc, needed to produce the favorable interaction with the induced velocity field of the main wing. At low flight velocities, winglet chords that are too small 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 the 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 the additional one of 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 not so critical, once the basic chord dimension has been determined, the spanwise chord distribution should be close to elliptical so that the induced drag over the winglet itself will be minimized. In addition, the elliptical planform will help the desired load distribution to be realized over a wide range of flight conditions. 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 consid-

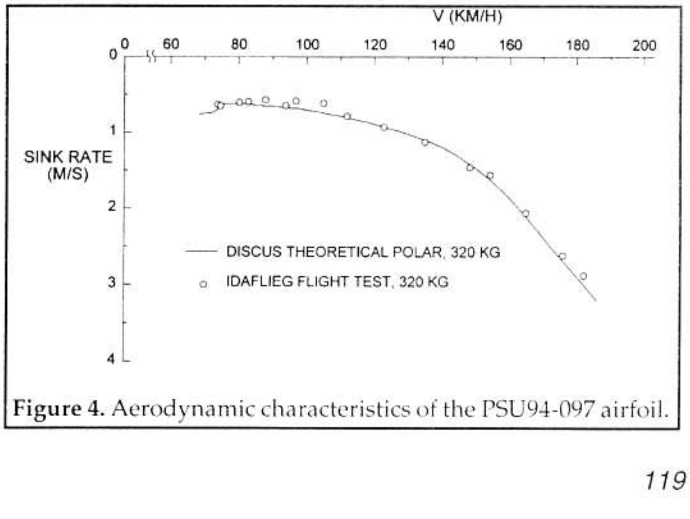

Figure 4. Aerodynamic characteristics of the PSU94-097 airfoil.

ering 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, fixing either one allows the other to be tailored to achieve the best overall performance.

After the planform has been designed, 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, the toe angle setting can 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 important element of the design process.

DESIGN APPROACHES

Past Methodologies

Several approaches to winglet design have been utilized at Penn State.[1-3] 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 can be termed the crossover point on the sailplane speed polar. This point corresponds to the velocity 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.

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 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 range of benefit, but also the magnitude of the benefit across the chosen range. Shifting the crossover to higher velocities reduces the magnitude of the winglet effect at lower speeds, while shifting the crossover to lower velocities allows a much larger benefit, but over a smaller region of the flight polar.

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. Thus, 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.

Present Approach

To address the limitations of the crossover point design methodology, a more comprehensive approach has been developed.[4] A fast, accurate prediction of the aircraft performance is combined with a thermal model, allowing the calculation of MacCready average cross-country speeds for specific weather conditions and aircraft parameters. This value 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 has been used often as a performance evaluator, these efforts have generally lacked the ability to accurately and rapidly assess very specific aircraft configurations. 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 aircraft 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, PGEN (Polar Generator), which has been developed to predict the straight and turning flight polars of sailplanes. To achieve the accuracy required, the PGEN 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 represents such a large portion of the overall drag that small errors in accounting for it can easily eclipse the effects of winglets. In order consider various flap configurations, the code must also be able to interpolate the airfoil aerodynamic characteristics over a range of flap deflections. In all, 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 aircraft flight performance is the determination of the wing planform span efficiency and lift distribution. The lift distribution directly effects 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 modified lifting-line code and a three-dimensional lifting-surface panel code. The lifting-line method, which has been integrated directly into the PGEN code, is that of Horstmann.[14] In this approach, the lifting line is divided into segments, each having a parabolic distribution of vorticity. 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 unable to discern all of the differences due to planform variations as can a panel method, this method is able to quantify the effects of winglets. For initial design iterations, the increased speed of the modified lifting-line method more than offsets the small loss in accuracy.

The use of the modified lifting-line program and the interpolation of airfoil characteristics allow PGEN to produce accurate straight and turning flight polars for any aircraft configuration. Comparison of predicted performance with Idaflieg flight test data for the Schempp-Hirth Discus[15] is presented in Figure 5. Other than near stall, the results agree closely with a maximum error in sink speed of less than two percent. Similar comparisons over a wide range of sailplanes have demonstrated that the method is able to resolve small enough differences between configurations to be of value in the winglet design effort.

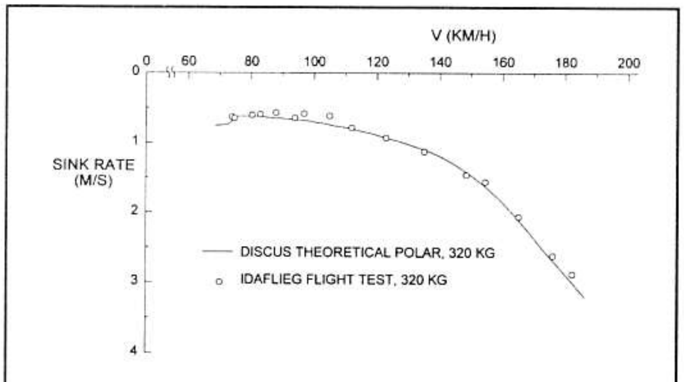

Figure 5. Comparison of predicted and flight-test results for the straight-flight polar of the Schempp-Hirth Discus.

For the final detailed design of the winglet, use is made of the program, PMFW (Panel Method for Windows).[1] This code takes free-wake effects into account. For the calculation of induced drag, use is made of the Kutta-Joukowsky theorem in the near field.[16] 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 small for the majority of the design effort, these differences can be significant in determining the final winglet toe and twist angles.[3]

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 design evaluator is desirable. This task is accomplished by a postprocessing program, called ACCEVAL (Average Cross-Country Speed Evaluator), which calculates MacCready cross-country speeds for a given configuration using the straight and turning flight polars generated by the PGEN program.[4]

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 realistic measure of performance would be the result of some particular mix of thermal strengths and profiles. 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 of 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.

EXAMPLE-DESIGN CASES

The first example to be considered is that of a winglet design for a Standard Class glider, the Schempp-Hirth Discus. The flight polars for an unballasted and ballasted Discus, with and without winglets, are presented in Figure 6. It can be observed that the winglets reduce the sink rate for the unballasted glider to airspeeds of almost 200 km/h. The addition of full ballast increases this crossover airspeed to greater than 220 km/h. This information is perhaps detailed better in Figure 7, in which the percentage gain in the lift-to-drag ratio as it depends on cruise velocity is shown. The crossover points, above which winglets hurt the sailplane performance, are seen to be greater than 200 km/h. The effect of winglets on the average cross-country speed is presented in Figure 8. The winglets improve the cross-country performance for all thermals considered, that is, for thermals having a 150 m

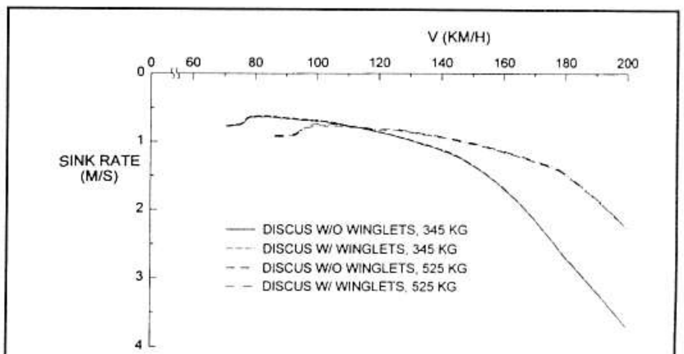

Figure 6. Straight flight polars of unballasted and ballasted Discus, with and without winglets.

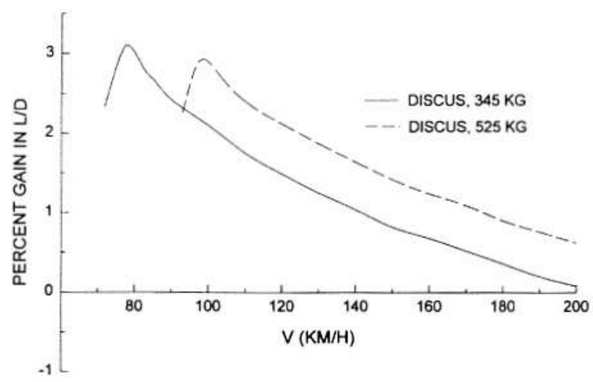

Figure 7. Percentage gain in lift-to-drag ratios due to winglets for unballasted and ballasted Discus.

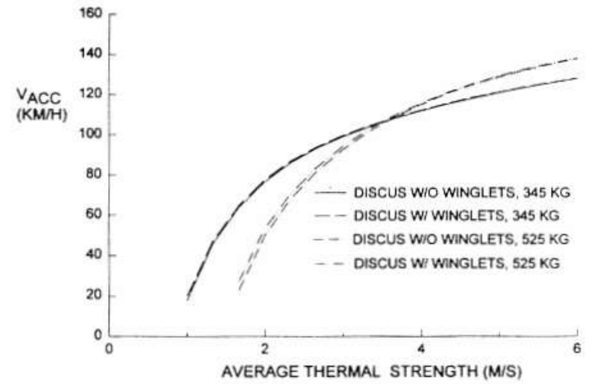

Figure 8. Average cross-country speed of unballasted and ballasted Discus, with and without winglets.

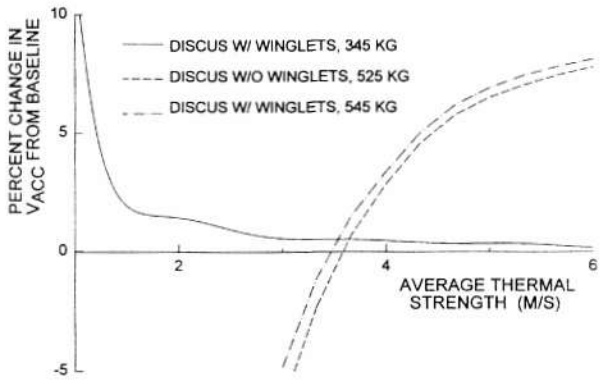

Figure 9. The percent change in average cross-country speed due to ballast and winglets relative to an unballasted Discus without winglets

radius and strengths, averaged across the diameter, of up to and greater than 6.0 m/sec. The point at which ballast becomes beneficial, at an average thermal strength of about 3.5 m/sec (corresponding to a ballasted climb rate of roughly 2.0 m/sec), is indicated on in the figures by the crossing of the unballasted and ballasted curves. Information such as this is detailed better by presenting the results as is done in Figure 9. In this figure, the percentage change in average cross-country speed relative to that of the baseline aircraft, without ballast and without winglets, is shown. In this case, the addition of winglets yields a gain in average cross-country speed over the entire range of thermal strengths considered. As expected, this gain is very significant for low thermal strengths in which the winglets allow the glider some climb rate whereas without winglets it is minimal or zero. As the thermal strengths increase, the benefit due to winglets decreases; however, for this glider winglets do not hurt cross-country speed even for average thermal strengths more than 6.0 m/s. As in the previous figure, ballast causes a reduction in average cross-country speed for thermal strengths of less than 3.5 m/s. For thermal strengths greater than this, winglets improve the cross-country speed, but only by one percent or less. Perhaps of more significance, the point at which ballast improves the overall performance is shifted by winglets from a thermal strength of 3.60 m/s down to 3.45 m/s. Thus, the glider with winglets is able to have the benefit of ballast over a slightly greater operational range than does the glider without winglets. Although this gain is small, such small differences can be an important factor in determining the outcome of many contest situations.

The second example to be considered is that of incorporating winglets on a Racing Class sailplane, the Schleicher

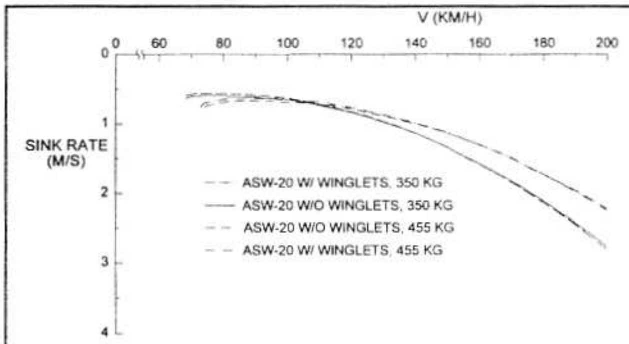

Figure 10. Straight flight polars of unballasted and ballasted ASW-20, with and without winglets.

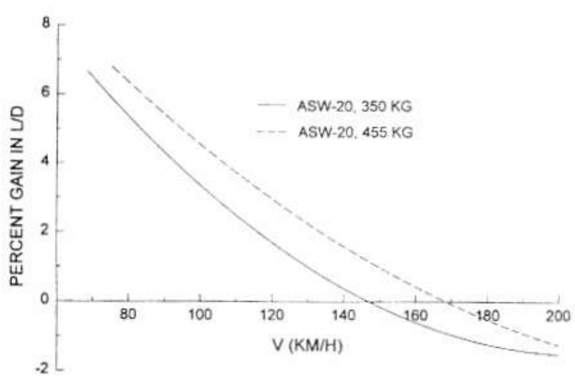

Figure 11. Percentage gain in lift-to-drag ratio due to winglets for unballasted and ballasted ASW-20.

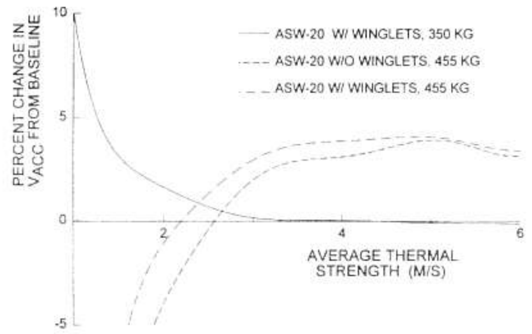

Figure 12. The percentage gain in average cross-country speed due to ballast and winglets relative to an unballasted ASW-20 without winglets.

ASW-20. In Figure 10, the influence of winglets on the flight polars of the ASW-20 is presented, while the percentage gain of lift-to-drag ratio as it depends on airspeed is plotted in Figure 11. In this case, the lift-to-drag ratio is increased by over six percent at low airspeeds and decreases with increasing airspeeds to a crossover points of 147 km/h without ballast and 167 km/h with ballast. The impact of winglets on the overall cross-country performance is better demonstrated, however, by comparing the average cross-country speed of the glider with winglets to that of the baseline aircraft without ballast and without winglets. This information is presented in Figure 12. As shown, winglets improve the performance of the unballasted glider for average thermal strengths of less than 3.0 m/s. For greater thermal strengths, winglets have little impact on the performance of the unballasted glider; however, for these conditions ballast should be carried. For the ballasted glider, winglets are shown to improve the average speed by about two percent for thermal strengths around 2.5 m/s, gradually decreasing and becoming negligible at thermal strengths greater than about 5.0 m/s. Again, it is perhaps of greater significance that the winglets reduce the minimum thermal strength for which ballast becomes beneficial from 2.6 m/s to 2.2 m/s. This significantly increases the range of conditions over which ballast can make an important difference in cross-country performance.

CLOSING REMARKS

Although the accuracy of design and analysis methods has been limited, the performance gains provided by winglets on a number of sailplanes have been clearly demonstrated. To help further these gains, a design methodology has been developed which has sufficient resolution to be of use in guiding the designer. The consistency of the results obtained thus far, and comparisons with flight-test measurements, are strong indicators that these methods are accurate in an absolute sense. This can be only truly determined, however, after more flight-test validation is performed, and after more long-term experience is obtained. In any case, it does seem clear that these methods are certainly accurate in that the proper trends and small performance differences between competing design candidates are correctly predicted. As a final comment, the experience thus far has shown that it is much easier to design winglets which harm the overall performance of a sailplane than it is to design those that produce an overall benefit.

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