the program accounts for the effects of airfoil characteristics, trim drag, static margin, flap geometry, and flap-deflection scheduling. The most important element of the method is the analysis of the wing-planform aerodynamics.

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

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

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

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

Analysis of Cross-Country Performance

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

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

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

Cross-Country Performance Gains: A Case Study

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

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

Other Considerations

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

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

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

Closing Comments

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

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

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

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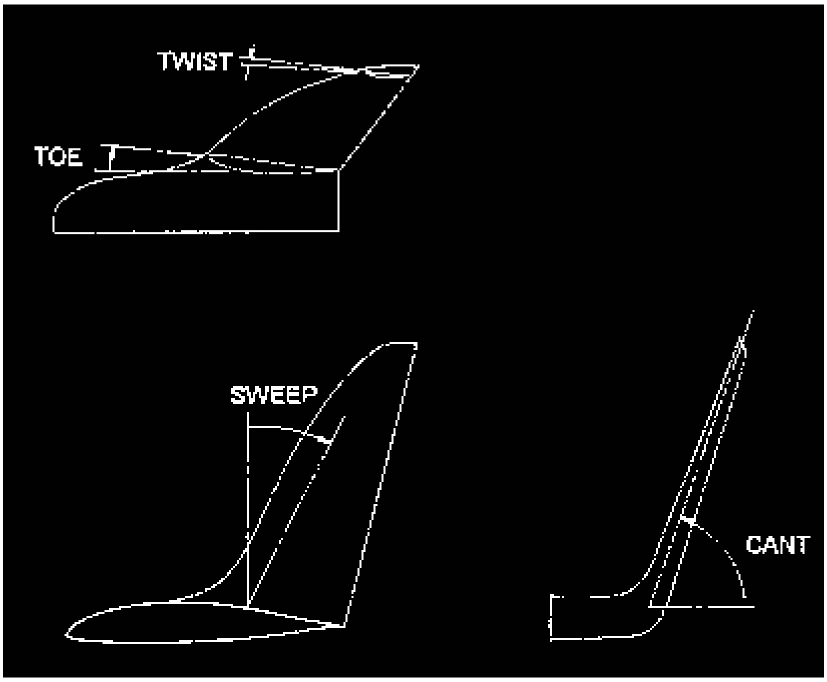

Fig. 1 Geometric quantities used to define a winglet.

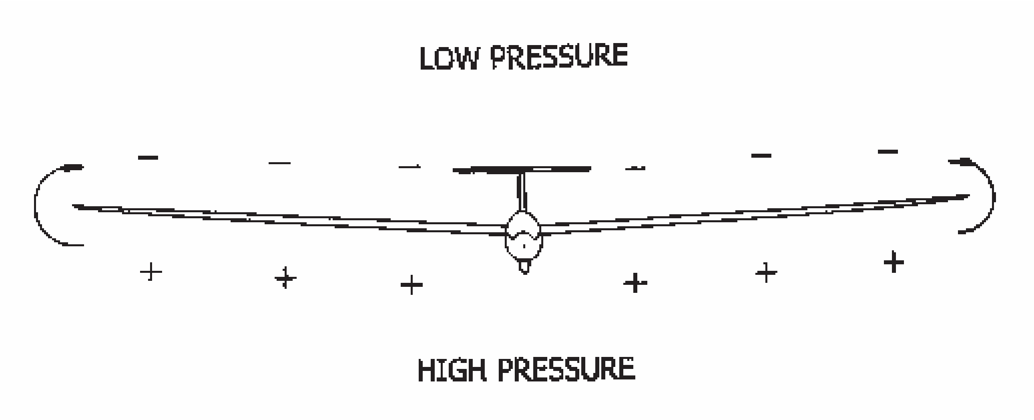

Fig. 2 Higher pressure air on the wing lower surface flowing around wingtip to upper surface.