ABOUT WINGLETS

by Mark D. Maughmer

Over the past ten years, from initially being able to do little to improve overall sailplane performance, winglets have developed to such an extent that few gliders leave the factories without them. They are now a familiar sight to nearly every soaring pilot. Few, however, really understand what winglets do.

Understanding Drag

A winglet's main purpose is to improve performance by reducing drag. To understand how this is done, it is first necessary to understand the distinction between profile drag and induced drag.

Profile drag is a consequence of the viscosity, or stickiness, of the air moving along the surface of the airfoil, as well as due to pressure drag (pressure forces acting over the front of a body not being balanced by those acting over its rear). As a wing moves through viscous air, it pulls some of the air along with it, and leaves some of this air in motion. Clearly, it takes energy to set air in motion. The transfer of this energy from the wing to the air is profile drag.

Profile drag depends on, among other things, the amount of surface exposed to the air (the wetted area), the shape of the airfoil, and its angle of attack. Profile drag is proportional to the airspeed squared. Readers interested in a more thorough explanation of these concepts are directed to refs. 1 and 2.

To measure an airfoil's profile drag in a wind tunnel, a constant-chord wing section is made to span the width of the wind-tunnel test section. In this way, the airflow is not free to come around the wing tips. There is thus no flow in the spanwise direction -- the wing section behaves as if it belonged to a wing of infinite span.

Induced drag is the drag that is a consequence of producing lift by a finite wing. If a wing is producing lift, there must be higher pressure on the underside of the wing than on the upper side. Thus, there is a flow around the wingtip from the high-pressure air on the underside of the wing to the low-pressure air on the upper side (fig. 1). In other words, there is spanwise flow on the finite wing that was not present on the infinite wing (fig. 2). This spanwise flow is felt all along the trailing edge as the flow leaving the upper surface moves inward while that on the lower surface moves outward. As these opposing flows meet at the trailing edge, they give rise to a swirling motion that, within a short distance downstream, is concentrated into the two well-known tip vortices. Clearly, the generation of tip vortices requires energy. The transfer of this energy from the wing to the air is induced drag.

This process can be idealized as a "horseshoe" vortex system (fig. 3). As a consequence of producing lift, "an equal and opposite reaction" must occur -- air must be given a downward velocity, or downwash. With this downwash comes spanwise flow, tip vortices, and induced drag. The goal is to minimize this drag by minimizing the amount of energy used in producing the required downwash -- to reduce the energy that is "wasted" in creating unnecessary spanwise flow and in the rolling up of the tip vortices.

In observing the flowfield around the wing in Fig.2, it should be clear that the greater the span, the less the tip effect is felt on the inboard portions of the wing. That is, the greater the span, the more "two-dimensional like" will be the rest of the wing and, consequently, the less its induced drag. As the span approaches infinity, the downwash and induced drag approach zero. Likewise, if the wing is not producing lift, there will be no downwash and thus no induced drag.

It is found that the induced drag is a function of the inverse of the square of the airspeed-- it is smallest at high speeds and increases as the aircraft slows down. It also depends on the weight squared divided by the span squared, $(W/b)^2$, how much weight each foot of wing is asked to support. Thus, it increases with the square of the aircraft weight and decreases with the inverse of the span squared.

Induced drag also depends on the wing design itself -- how efficiently it produces lift. As a reference point, the most efficient planar wing (a wing with no dihedral or a winglet) is one that has an elliptical loading (greatest at the root and decreasing toward the tip, following the equation of an ellipse). Typical planar wings are slightly less efficient, while non-planar geometries can be somewhat better than the elliptical case.

Controlling Induced Drag

It has been known for over a century that an endplate at the tip of a finite wing can reduce spanwise flow and induced drag. Unfortunately, to be effective at this, the endplate must be so large that the increase in skin friction drag due to excessive wetted area far outweighs the reduction in induced drag.

A winglet provides a way to do better.[3] Rather than being a simple "fence," it carries an aerodynamic load. The idea is to produce a flowfield that interacts with that of the main wing to reduce the amount of spanwise flow. That is, the spanwise induced velocities from the winglet oppose and thereby cancel those generated by the main wing.

This effect has been measured experimentally (Fig. 4). Here it is observed that the spanwise flow has been largely eliminated by the presence of the winglet. In essence, the winglet diffuses or spreads out the influence of the tip vortex such that the downwash, and thereby the induced drag, is reduced. In this way, the winglet acts like an endplate in reducing the spanwise flow but, by carrying the proper aerodynamic loading, it accomplishes this with much less wetted area. Nevertheless, recalling the penalty of profile drag with increasing airspeeds, the designer's goal is to gain the most reduction in induced drag for the smallest increase in profile drag.

The Winglet Design Process

My involvement began over a decade ago when I was asked by Peter Masak to help in the design of winglets for the then-current crop of 15-meter racing sailplanes. Early design procedures were based on the idea of a crossover point -- a breakeven airspeed below which winglets improves performance by reducing induced drag and above which their extra wetted area adds enough profile drag that performance is lower. Our first successful winglets for sailplanes were guided by this notion. A trial-and-error approach was employed that eventually led to some significant improvements.[4] In 1989, one of these designs was adopted by Schempp-Hirth as the "factory winglet" for the Ventus. In retrospect, with the understanding that has come since, it seems that this process, while systematic and logical, was accompanied with a great deal of luck. It now seems somewhat remarkable that with the tool then at hand, we were able to come up with a design that worked so well.

In spite of some success, I was somewhat frustrated by the lack of tools then available to analyze or design winglets. Thus, along with a succession of excellent students, a research effort was begun at Penn State to better this situation. In 1994, a collaborative research arrangement with M&H Soaring (Monty Sullivan and Heinz Weissenbueller) in Elmira, New York was begun. Their close proximity to Penn State, along with their acceptance that it would not be a trivial matter to fabricate and flight test the number of trials needed to develop and validate sound design methods, resulted in a fruitful and enjoyable cooperation that continues still.

As our ability to predict the induced drag for a given wing geometry improved,[5] so did the ability to predict the effects on sailplane performance due to small changes in geometry. With this, it became possible to design winglets that much more closely achieved the intended results.

Some rules-of-thumb were established. First, whether it be with up-turned tips or winglets, it can be beneficial to go "out-of-plane." Second, while a great deal of work has been directed toward achieving the minimum induced drag,[6] our experience is that driving a winglet toward this optimum penalizes the profile drag far more than it benefits the reduction in induced drag. The design goal is clearly to minimize the overall drag, not just the induced drag.

The cross-country performance of a sailplane can now be predicted with enough accuracy to determine whether small changes in winglet geometry are beneficial or not. To do this, straight flight and turning speed polars are calculated, including the influence of variations in the spanwise lift distribution over the speed range, profile drag of the aerodynamic surfaces as they depend on Reynolds number, flap deflections, and trim drag.[7] Optimum flap settings over the speed range are also computed. These results are then used to predict average cross-country speeds in given weather conditions. After the optimum bank angles are determined for a range of thermal strengths, sizes, and lift profiles, a MacCready climb/glide analysis shows the average cross-country speed of the glider as a function of thermal strength. So rather than design the winglet to simply not hurt the lift-to-drag ratio below a certain airspeed, the winglet can be tailored to give the best cross-country performance over a wide range of operating conditions.

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. 5. Although gains are demonstrated, they are difficult to assess using the polars shown. Thus, the data are replotted in terms of L/D verses velocity in Fig. 6. In addition to demonstrating the gains from 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.7 these data are again replotted in terms of the percentage increase in L/D relative to the unballasted and ballasted glider without winglets. Note how this winglet's crossover point occurs at airspeeds that are above the maximum allowable -- there are no allowable flight conditions in this case for which the winglets penalize performance. Although a slight overall gain could be achieved by tailoring the winglet more for climb, this would result in relatively large penalties at high speeds. While the percentage gain in L/D does not appear to be very great, it is significant that it comes without any penalty at higher speeds.

The effect of winglets on the percentage change in average cross-country speed relative to that of the baseline aircraft is presented in Fig. 8. The winglets improve the cross-country performance for all the thermals considered, that is, for thermals having a 500’ radius and strengths of up to 12 kts. As expected, the performance gain is very significant for weak thermals -- having winglets allows for some climb rate, whereas without them it is minimal or zero. As the thermal strengths increase, the benefits decrease; however, for this glider winglets do not hurt cross-country speed even for average thermal strengths of more than 12 kts.

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, corresponding to a climb rate with full ballast that is predicted to be about 5.2 kts. In this case, “full ballast” corresponds to a wingloading of 10.6 lbs/ft^2 rather than the 9.0 lbs/ft^2 allowed by U.S. Standard Class rules. As indicated, ballast causes a reduction in average cross-country speed for average thermal strengths of less than 8 kts. For thermal strengths greater than this, winglets improve the cross-country speed, but only by a half-percent or so. The glider with winglets, however, can profitably carry ballast in slightly weaker conditions than can the glider without winglets.

Other Issues

From the experience of designing winglets for a variety of sailplanes (as well as for a few non-sailplane applications), it seems 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).

It is sometimes heard that winglets were tried on a certain glider and did not work. What this really says is that a particular poor design did not work. As an example of how critical some of the design issues are, the effect of toe (incidence) angles on the Discus 2 winglet design is presented in Fig. 9. Obviously, a small deviation from the optimum can cause the winglet to become a speed brake. Furthermore, each glider must have winglets specifically designed for it -- rules of thumb can be disastrous. From personal experience, there is no doubt that it is much easier to make a glider worse with winglets than it is to make it better!

Winglets sometimes can fix problems of the original wing. For example, in the case of a flapped glider, it is important that the flaps/ailerons extend to the wingtip. Otherwise, when the flaps are deflected upward for high-speed cruise, the tips are loaded far more than they should be. Although only a small portion of the wing is influenced, it can result in a very significant induced drag increase. In these cases, cutting the tip back to the aileron in order to mount the winglet has resulted in unexpected gains, especially at high speeds.

By understanding of how winglets achieve induced drag reduction, it also becomes clear how they can produce other performance and handling gains. 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, and by 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 means less drag for a given roll rate and a higher maximum roll rate. Likewise, woolen tufts attached to glider wings have shown that much of the flow over the inside tip during turning flight is separated, which is nearly eliminated by the presence of a winglet. Winglets also benefit safety -- ailerons remain effective much deeper into a stall than before.

The improvement in handling qualities are very succinctly described by Werner Meuser, the current 15-Meter Class World Champion, in a message sent to me by the Schempp-Hirth factory describing his first impressions of the new Ventus 2ax winglets. "…..very impressed by the handling change. He reported the glider got more gentle and harmless at low speeds and felt very 'clean' close to stall speed., which seems to have decreased remarkably. Even in steep circles, there was no tendency to stall or 'misbehave'. Before anything at the wing started to separate, he felt the tailplane couldn't handle the angle of attack anymore. Allover, very positive impressions…."

Conclusions

Although 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 and contests. For example, in the 1999 U.S. Open Class Nationals, just 68 points separated the first six places. This difference amounted to less than 1.5% -- far less than the performance advantage that can be achieved using well-designed winglets.

Since their shaky introduction many years ago, the acceptance of winglets is now widespread. At the World Championships in Uvalde, Texas in 1991, of 105 competing gliders, 19 used winglets. At the most recent championships in South Africa, essentially every glider entered had winglets or some type of tip treatment.

Thus, after more than 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 little consequence over the range of airspeeds 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, testing has not been extensive. The anecdotal evidence indicates that gliders with winglets are more reluctant to spin, but once they do, the altitude required for recovery is somewhat greater. Given that many glider fatalities are a consequence of stall/spin accidents during approach, at altitudes from which safe recovery is not possible, a question worth pondering is whether even the most basic training gliders might benefit from the installation of winglets.

References

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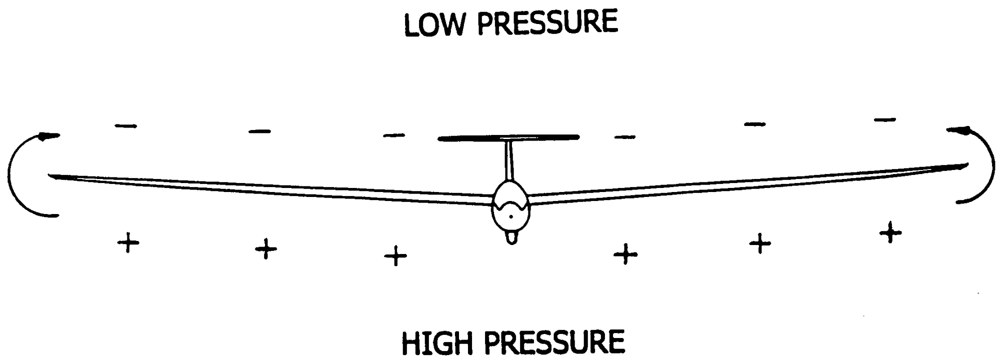

Fig. 1 Higher pressure air on the wing lower surface flowing around wingtip to upper surface.

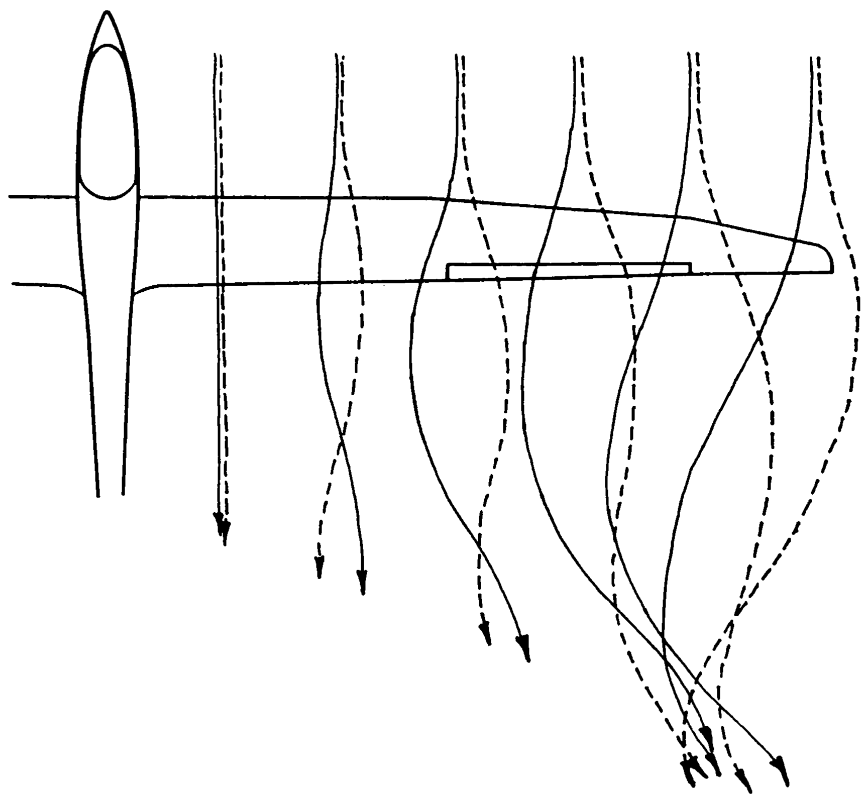

Fig. 2 Spanwise flow on a finite wing - solid lines, upper surface; dashed lines, lower surface.

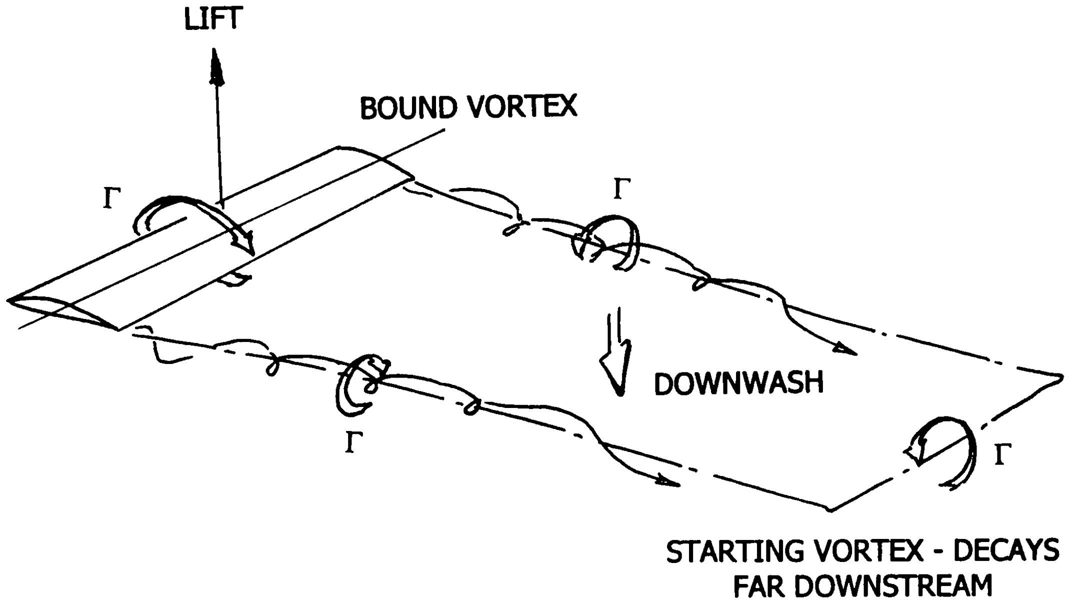

Fig. 3 Idealized "horseshoe" vortex system.

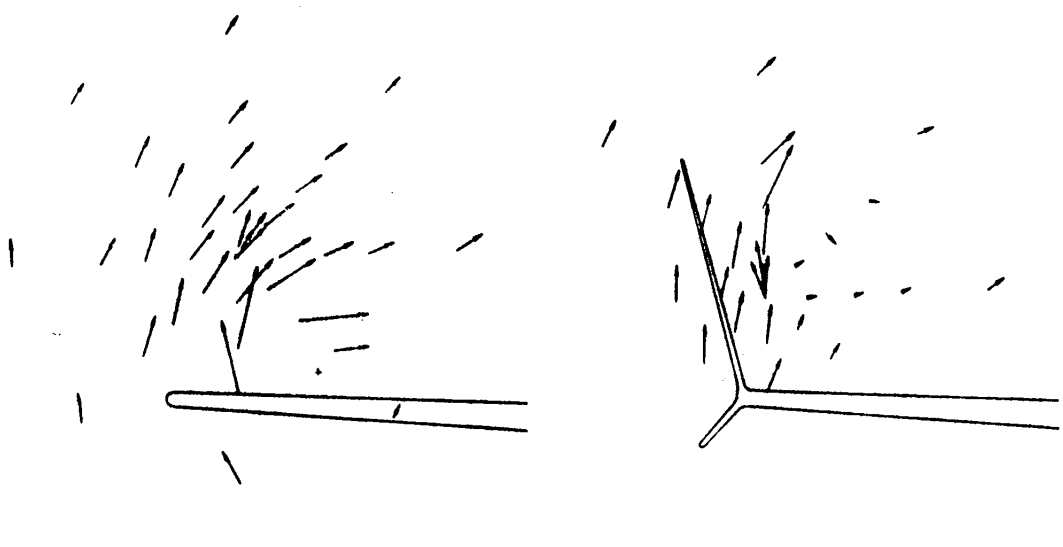

Fig. 4 Experimentally determined flowfield crossflow velocity vectors behind model with and without winglets.[6]

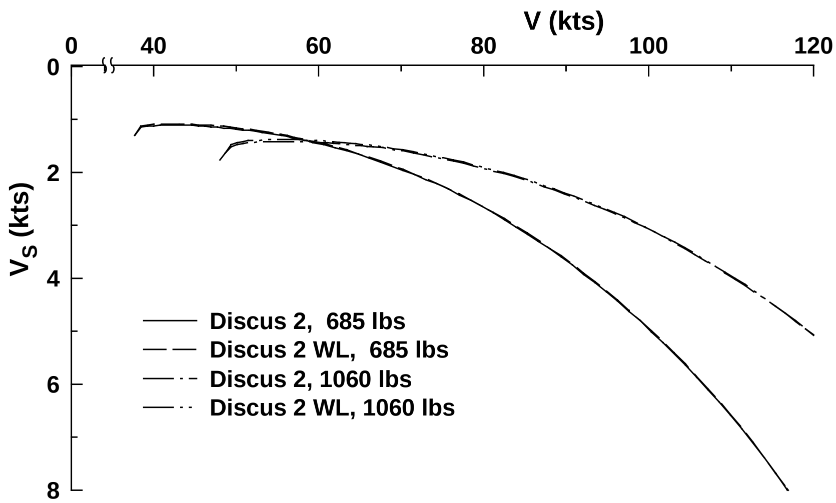

Fig. 5 Predicted straight flight polars of unballasted and ballasted Discus 2, with and without winglets.

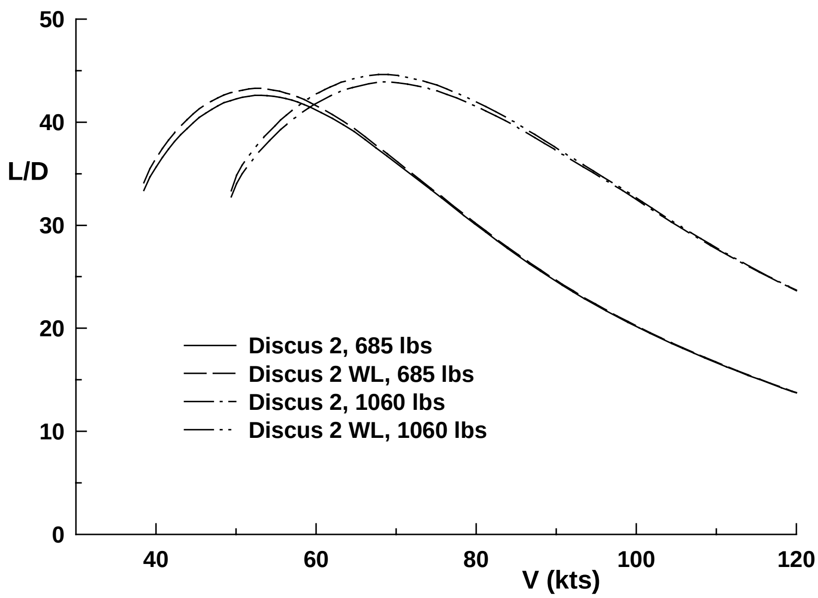

Fig. 6 Comparison of predicted lift-to-drag ratios for unballasted and ballasted Discus 2, with and without winglets.

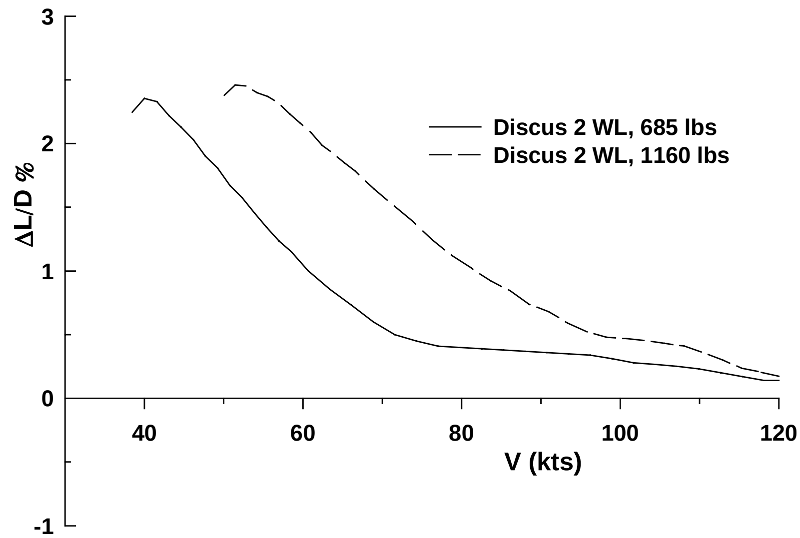

Fig. 7 Percentage gain in predicted lift-to-drag ratios due to winglets for unballasted and ballasted Discus 2.

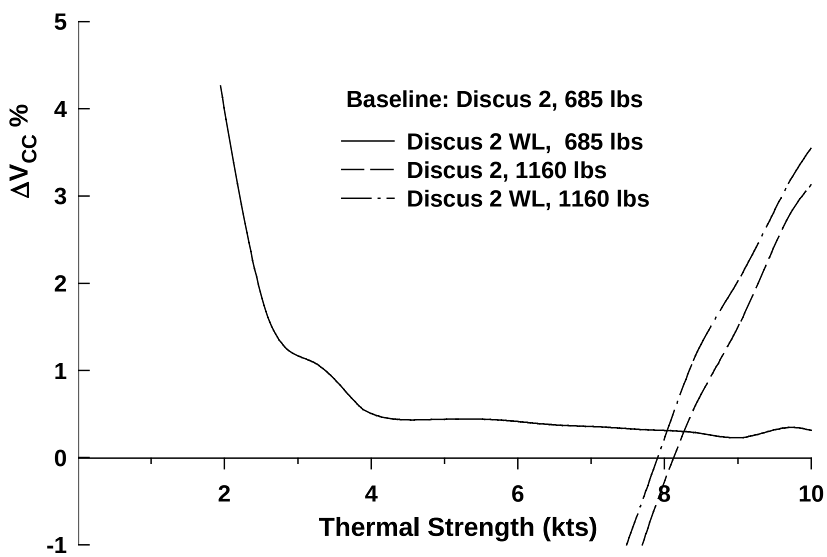

Fig. 8 Percentage gain in predicted average cross-country speed due to winglets and ballast relative to unballasted Discus 2 (685 lbs) without winglets.

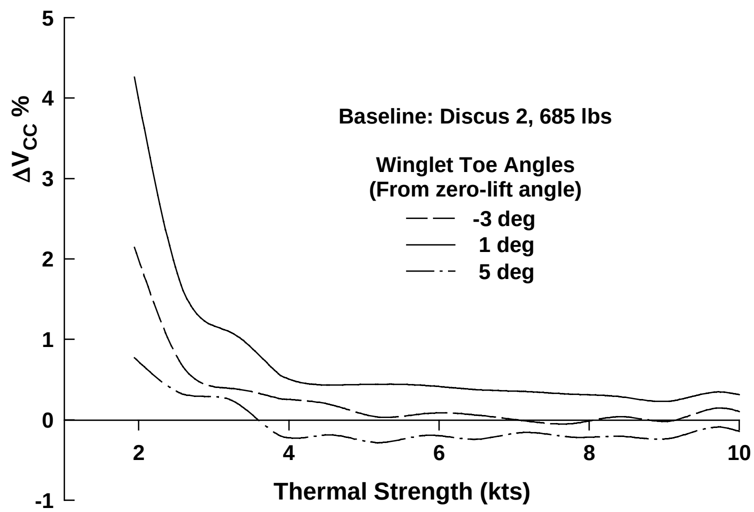

Fig. 9 Percentage change in predicted average cross-country speed as it depends on winglet toe angle for an unballasted Discus 2. Toe angles are measured relative to the zero-lift angle of attack.