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DESIGN AND DEVELOPMENT OF THE SWIFT: A FOOT-LAUNCHED SAILPLANE

Ilan Kroo*
Stanford University
Stanford, CA 94305

Abstract

This paper describes the development of what might be considered the first successful ultralight sailplane. The SWIFT is a high performance foot-launched glider, designed to combine some of the convenience of hang gliders with the soaring performance of sailplanes. It takes off and lands like a hang glider, yet maintains exceptional performance at high speeds, achieving a lift-to-drag ratio of about 25:1. Although it is a fully-cantilevered rigid wing with aerodynamic controls and flaps, it is light enough to launch by running from a hillside and is easily transported on the top of a car. This paper describes the design, development, and flying of this unique aircraft.

Introduction and Background

Pioneers of heavier-than-air flight were inspired with the idea of being able to fly like birds – not for the purpose of efficient, high-speed transportation, but for the shear freedom that such a capability would permit. This was the motivation for, and is the appeal of, modern soaring aircraft such as paragliders, hang gliders, and sailplanes. Although the performance of sailplanes has increased dramatically over many decades so that lift-to-drag ratios of 60:1 have been achieved and 1000 km flights are possible, certain aspects of high performance sailplanes seem counter to the vision espoused by Lilienthal and others [1]. Especially for a group of graduate students in the San Francisco Bay Area, the cost of sailplane flying, along with the long drive to an airport that supported such activities, meant that achieving the goal of bird-like flight was only somewhat more realizable than it was 100 years ago. That one was often restricted to flights near this airport also made the reality of soaring somewhat less inspiring than the vision. This, of course, was one of the reasons that the sport of hang gliding became popular. But while hang gliding avoided many of the problematic aspects of sailplane flying, it introduced new difficulties. Hang gliders were inexpensive and could be flown from many local sites, but their performance was such that long distance flights were uncommon. Flying was often restricted to a very small corridor on a ridge, and more often than not, consisted of an unimpressively short glide to the bottom of the hill. Furthermore, the simple, yet subtle, techniques for hang glider control using pilot weight-shift seemed to limit further performance improvements and led to less than ideal handling qualities under some flight conditions.

In 1985, I recruited a group of outstanding graduate students at Stanford, many of whom were hang glider or sailplane pilots, to investigate what was possible at the boundary between these two aircraft types. The idea was to consider the possibility of an airplane that would fly at the speed of birds, permitting launching and landing like a hang glider, yet with the performance and control that would permit extended soaring flights on good days. With affordable computational aerodynamic analysis capabilities improving, composite structures evolving, and with some specific concepts for efficient tailless aircraft configurations, we began the design of a foot-launched sailplane that would eventually become the SWIFT.

Of course, we were not the only ones working on such ideas. Designs such as the Mitchell Wing, the Canard 2FL, and lightweight sailplanes inspired by the SSA's homebuilders' workshops suggested that such an airplane might be feasible. Of particular relevance was the work of Brian Robbins, Erik Beckman, and Brian Porter of BrightStar Gliders, just two hours North of Stanford. BrightStar had been developing a rigid wing hang glider, called the Odyssey, which Brian Porter piloted to first place in the 1989 U.S. National Hang Glider Championships. Brian Robbins suggested that the Stanford group might improve the Odyssey's airfoils somewhat; but after several evenings of discussions, we agreed to pursue a radically new design. Four months later, in December of 1989, the SWIFT took to the air over a small hill in Marin County.

This paper describes the technical development of the SWIFT, with a focus on the aerodynamics design

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* Professor, Dept. of Aeronautics and Astronautics, Associate Fellow AIAA

concepts unique to this configuration and aircraft class. Additional descriptions of the evolution of this design may be found in [2,3,4].

Figure 1. SWIFT on approach.

Design

Objectives

The design of the SWIFT began with a study of the requirements for cross-country soaring. Based on surveys of thermal distribution and strength and inter-thermal downdrafts from [5], we developed a cross-country soaring simulation that would permit changing glider parameters and evaluating the effect on the likely achievable soaring distance. Even without this simulation on could see the direction required for extended soaring (see [6]). From data on 76 thermals encountered in Dick Johnson's flights over eastern Texas and from our own experience in California and Nevada, we created a statistical distribution of thermals that were spaced 1.2 to 12 miles apart with heights of 1600 to 7000 ft. The interthermal sink varied from 1.4 to –0.3 kts with an average of 0.3 kts and with 80% of the cases less than 0.5 kts. Based on this model one could compute the probability of reaching the next thermal – or of flying 100 miles. This is shown in the table below as a function of the effective interthermal glide slope.

Effective Glide Slope	P(next thermal)	P(100 mi)
10	.37	10^{-7}
15	.81	.034
18	.91	.21
20	.95	.44
40	nearly 1	nearly 1

It is clear that inter-thermal glide ratios of at least 15 to 18 in the presence of the assumed 0.5 kts of sink is needed to make this kind of soaring easily attainable. At the time that this study was first made time, only a dozen 100 mile flights had been made by hang gliders. Today, although flights over 300 miles have been made, most pilots (even most advanced pilots) have not flown 100 miles. One of the factors limiting the flight distances of hang gliders is their speed. The effective inter-thermal glide slope in the presence of sink is much lower for slow-flying aircraft. The table below shows the aircraft lift-to-drag ratio required to achieve and inter-thermal glide slope of 18:1 in the presence of a 0.5kt downdraft (or 9 kt headwind).

Cruise Speed (kts)	L/D Required
10	180.0
20	32.7
30	25.7
40	23.2
50	22.0
60	21.2
80	20.3

Furthermore, thermals are commonly encountered for a rather limited time during daylight hours and with average cross-country cruising speeds of less than 20 kts, one needs to fly for five hours to go 100 miles. Thus, extended cross-country soaring requires not only a good enough glide to make it to the next thermal, but a fast enough glide to get there quickly and in the presence of headwinds or sink. This is easily done by making large span sailplanes with high wing loading. But if the glider is to be foot-launched, it must be light (span not too large) and have a low wing loading. More refined studies of Johnson's data and barograph records from George Worthington's Mitchell wing flights in the Reno area suggested that a foot-launched sailplane with the required performance was just barely possible. The following target performance figures were established and work began to define the aircraft geometry.

Target Performance for Foot-Launched Sailplane

1. Minimum Sink Rate in 100' radius turn: 200 fpm
2. Maximum L/D: 20:1
3. L/D at 60kts: 15:1
4. Stalling speed: no higher than existing hang gliders for safe foot-launching and landing
5. Weight: less than 90 lbs
6. Exceptional controllability for safe flight at low speeds

The fourth constraint meant that even with large flaps, the wing area would be 120 to 140 sq ft. With this constraint, the third goal would be very difficult, requiring an unprecedented level of aerodynamic streamlining. To achieve the desired performance, low drag airfoils and an extremely clean pilot fairing would be required. The sink rate polars in figure 2 illustrate the importance of streamlining, especially for light weight gliders at high speed. The figure also shows how the predicted sink rate of the SWIFT compares with other gliders; it is clearly in a class above hang gliders and compares very favorably with the Schweizer 1-26 sailplane at speeds up to about 60 kts.

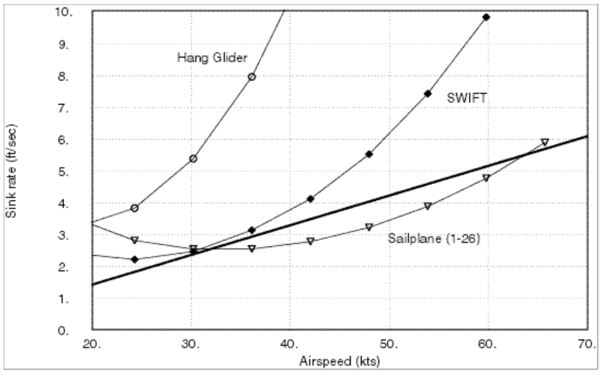

Figure 2. Sink rate polar comparison for some soaring aircraft.

Conceptual Design / Configuration Concept

Unless one does something very wrong, the performance of a glider is determined primarily by its weight, span, area, and streamlining. The selection of the configuration, whether conventional, canard, tailless, or something else, is based more on issues such as packaging, handling qualities, manufacturability, transportability, etc.. In the development of the SWIFT, several possible configurations were studied. The results indicated very small performance differences between tailless, conventional and canard designs; however, the conventional design suffered some from the short tail length required for landing flair and take-off ground clearance. The directional stability of a slightly-swept canard was poor, and performance was also compromised by the short coupling. The tailless design was statically-balanced (empty c.g. near flight c.g.), compact, and did not pay the weight penalty that would be associated with a tail boom. (Note that even a 5 lb boom represents more than 5% of the empty weight and a very large fraction of the wing bending weight.) For these reasons, and to study several aspects of tailless aircraft design, an aft-swept “flying-wing” design was selected.

One of the first steps in the configuration development was a sizing study that started with a look at the sensitivities of performance to several design parameters (see figure 3). This was followed by a more comprehensive optimization of span and area based on the cross-country soaring simulation.

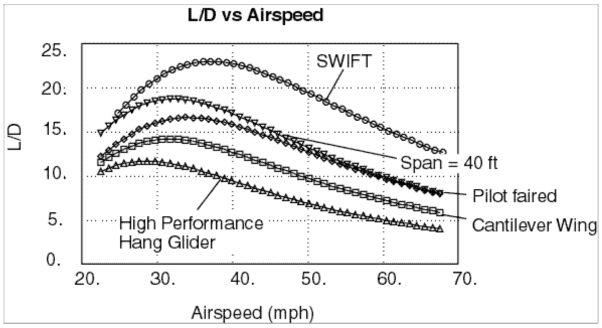

Figure 3. Effect of design parameters on lift-to-drag ratio.

As the design evolved, several mock-ups were constructed to evaluate visibility and ground-handling. A high wing arrangement was adopted for good ground clearance and pilot visibility, with an arrangement similar to that used by the Odyssey. On the ground, the glider is supported by shoulder straps (Fig. 4).

Figure 4. Glider is supported by shoulder straps prior to launch.

After takeoff, the pilot rotates his or her legs forward into the aluminum cage structure. The pilot is supported by a retractable sling that provides a comfortable reclined orientation. (Fig. 5). The glider may be flown with a fairing that covers the cage structure, or with the pilot exposed to the air. Subsequent SWIFTs have included a small wheel and skid that permits feet-up landing when conditions permit and even towed launches.

Figure 5. The pilot rotates into flying position supported by a retractable sling.

Aerodynamic Design

The S.W.I.F.T. Concept

Although the tailless configuration is common among hang gliders, for which portability is paramount, tailless designs are often considered an aerodynamic compromise. Textbooks have noted the poor maximum lift capability of flying wings and some penalty is generally assumed to be associated with trim, whether through less-than-optimal reflexed airfoils or twist-related drag. Handling qualities have also been undesirable for many aircraft of this configuration. It was our goal then to see if we could minimize or eliminate these difficulties by careful 3-D aerodynamic design of the wing. The combination of sweep, taper, and twist was arranged so that rather conventional airfoil sections with negative pitching moments (not reflexed airfoils) could be used (see following section).

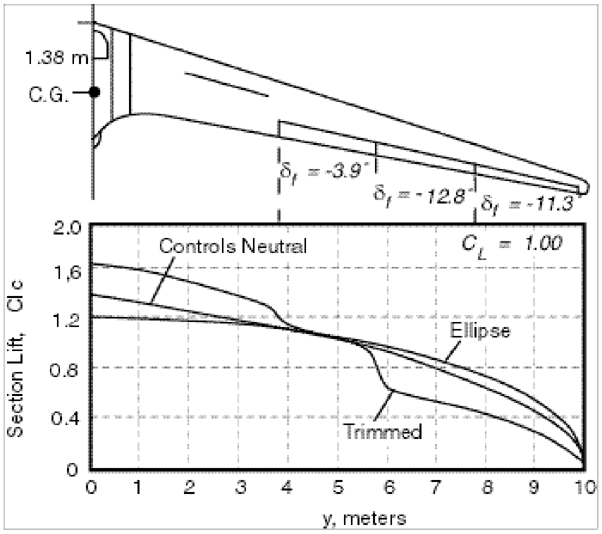

Figure 6. Horten VI planform and lift distributions

The use of sweep and twist, rather than section properties, to achieve pitch trim on a stable tailless aircraft is well known. It is used by most hang gliders and on the well-known tailless sailplanes developed by the Hortens[7]. The penalties associated with such wing twist can be large as evidenced by the Horten IV whose spanwise lift distribution is shown in figure 6. When trimmed at a lift coefficient of 1.0, considerable upward deflection of the elevons is required leading to lower section C_{lmax} and an induced drag penalty. The SWIFT was designed to maintain very close to the ideal lift distribution when trimmed, effectively eliminating such penalties.

The basic idea is that a swept wing can be stable and trimmed, even with elliptic loading if the planform shape is properly chosen. What is required is that the center of lift associated with changes in angle of attack (the aerodynamic center) must be located outboard (hence aft) of the actual center of lift. If the wing is elliptically loaded, the center of lift is located at 42.4% of the semi-span. This is fixed. But the aerodynamic center can be moved farther outboard by increasing the sweep and tip chords. With typical airfoil sections, it is possible to move the center of additional lift (a.c.) sufficiently far from the center of total lift to achieve reasonable static margins with moderate sweep and taper, as long as the aspect ratio is sufficiently large. Another way to think about this effect is to imagine adding the lifts of an untwisted wing at angle of attack with that of a twisted wing at zero lift. Although the induced drag penalty of each of these components is large, the sum provides an ideal lift distribution without trim penalty (Fig. 7). The planform of many tailless aircraft incorporate sweeps and tapers that are not consistent with this concept.

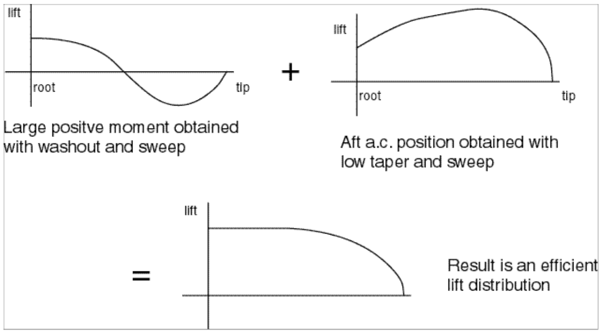

Figure 7. The combination of washout and a tip-weighted additional load distribution produces a desirable net loading.

Like any stable, swept tailless airplane, the SWIFT requires more effective twist to trim at higher angles of attack. This is not necessarily a penalty as the planform is designed to require more twist at higher angles of attack to achieve the ideal span loading. However, the use of elevons to achieve this effective twist change is problematic for several reasons. One of the fundamental ideas behind the SWIFT control strategy is to deflect an inboard surface downward, rather than an outboard surface upward to achieve trim at higher C_L. Such approaches were discussed by Lippisch and others many decades ago [8,9], but have been used to great effect on the SWIFT. By deflecting the inner flap downward one increases the effective wing washout as desired, but also increases camber and maximum lift. (Fig. 8). Because of the moderately tapered planform, the SWIFT can exploit a trim-changing flap that covers about 45% of the wing span. When deflected down for higher lift, the glider noses up slightly and trims at a lower speed. It may be deflected downward as much as 55° for landing and approach, reducing the L/D to a manageable value and slowing the glider down for stand-up landings. This use of the inboard flap for pitch trim gives the aircraft its name. At the risk of confusion with the long line of Swift aircraft, this SWIFT stands for Swept Wing with Inboard Flap for Trim.

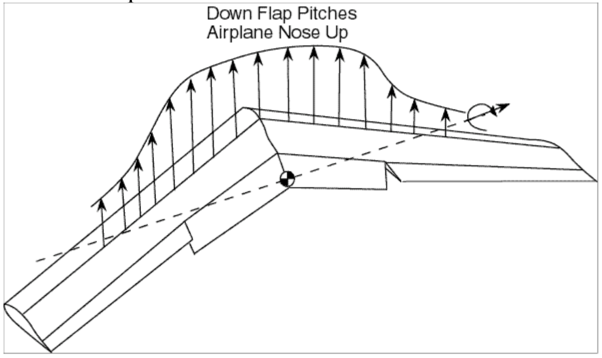

Figure 8. The inboard flap produces nose-up trim despite the large negative section moments.

Wing Optimization

The next step in the SWIFT's aerodynamic design involved complex trade-offs between wing taper, twist, flap size, flap deflections, elevon deflections, and wing area. Changes that might benefit high-speed performance might hurt thermaling ability or increase stall speed above acceptable limits. The final trade-offs were made by simulating a long cross-country flight on the computer and using a numerical optimizer to select the design with the best overall soaring performance. The simulation included thermal models, inter-thermal sink, and a 3D inviscid aerodynamic analysis (panel model) of the design. The resulting configuration is shown in figure 9.

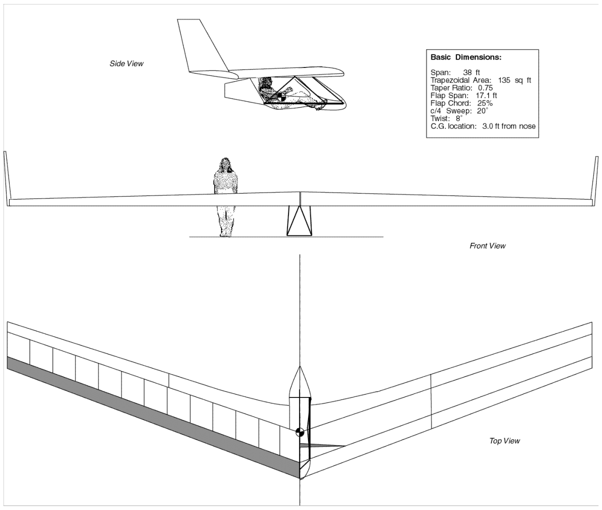

Figure 9. 3-View Layout of SWIFT

Airfoil Development

Airfoils were designed especially for the SWIFT. The sections have a small negative pitching moment and were designed to operate in the Reynolds number range of 700,000 to 2,000,000. They make use of laminar flow over the first 25% of the chord, if they can get it, but are explicitly designed to experience little performance degradation if the flow is made turbulent by rain or surface irregularities. This amount of laminar flow was selected based on the idea that the first 25% of the airfoil could be quite smooth and accurately constructed. The airfoil thickness at the flap and elevon hingelines was originally quite large to provide strength in this area. Tests on the first prototype suggested that the strength in this region was not a problem, but the gaps created by control deflections added a great deal of drag. The airfoils were redesigned with very thin trailing edges that successfully reduced the control surface gap drag. Except for the analysis of these sections using simple airfoil design programs on Apple Macintoshes, the airfoils were not tested before the first prototype was built. Truck-mounted tests of the glider suggested that the airfoils are working as predicted, but accurate performance verification was not done as it was not considered critical in the aircraft's development. The main airfoil geometry is shown in figure 10. The maximum thickness is large and is located quite far forward in consideration of the wing structural constraints. The greatest challenge in the airfoil design was to achieve a very large C_L range and to ensure that the section would operate efficiently with the inboard flap. Figure 10 shows the section C_p distribution at lift coefficients of 0.2 and 1.4. The section achieves laminar flow over approximately 25%-30% of its chord – not extensive by sailplane standards, but a reasonable compromise to achieve the weight goals.

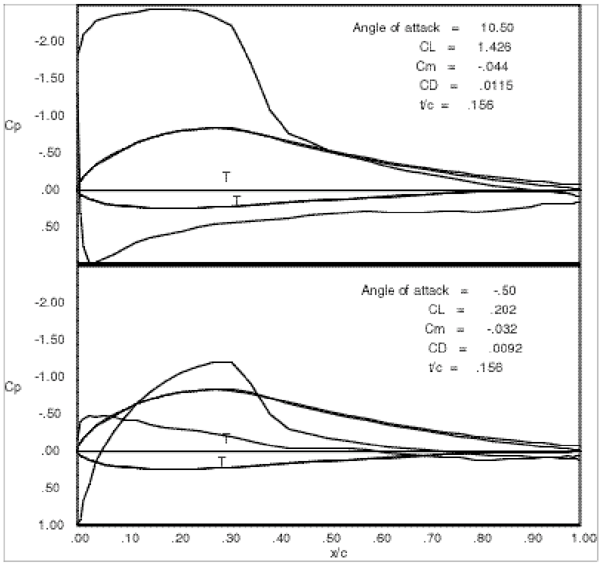

Figure 10. Airfoil pressure distributions over a large range of lift coefficients.

Structural Design

The structure of the SWIFT is designed to meet the demanding requirements of very low drag (fully cantilevered, accurate airfoil definition for laminar flow) and light weight. The wing structure uses a D-tube covering the first 25% of the chord with ribs extending from there back to the control surface hinge line at 75% chord. The prototypes were constructed with an Aluminum D-tube and mylar covering to reduce costs and one-off construction time. This made it possible to refine the design before committing to the molds from which production versions were built. The basic structural concept is shown in figure 11. Using Kevlar skins and graphite spar caps, the vehicle empty weight is about 100 pounds, although with full fairing, rocket-deployed recovery parachute, and instruments the weight becomes somewhat greater than we had originally envisioned. In a light breeze, however, the wing lifts itself and the weight that must be borne by the pilot's shoulders is quite manageable.

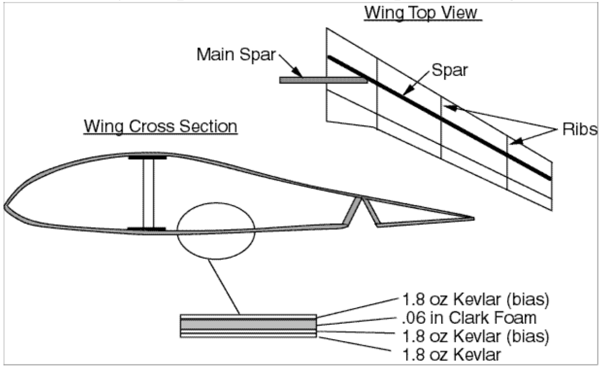

Figure 11. Structural concept.

The loads that need to be carried by the glider itself, though, are very large. Because of the low wing loading and high design airspeeds, the effect of gusts is amplified. To comply with FAA sailplane criteria the glider must be capable of withstanding positive and negative vertical gusts of 24 ft/sec up to VNE. Since the maximum speed of this sailplane is above 60kts, the required limit load is about 6 g's (see Fig. 13). The prototypes were static loaded to 5 g's to be sure that they could be test flown. Subsequent successful static load tests were made up to 9 g's.

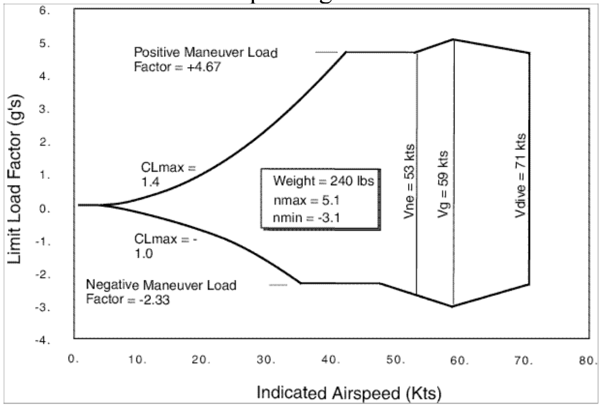

Figure 12. Initial V-n diagram. Note high gust loads.

Stability and Control

One of the major goals of this project was to provide vastly improved handling qualities to a foot-launched glider, and many of the SWIFT's features were designed to improve stability and control. The large tip chord provides additional pitch damping to increase the aircraft's dynamic stability and reduce the possibility of tumbling in extreme conditions. It also gives the elevons increased control authority especially at low speeds. The use of aerodynamic pitch controls (actuated by a side-stick controller) makes it possible to trim the glider over a very large speed range without large stick forces or low stability and gives the pilot positive control in very rough conditions when weight shift would do little good. The stalling characteristics are also improved by the moderate taper, high effective twist, and vortilons – vortex generators originally invented in the development of the DC-9 [10]. The fixed pilot position and relatively short vertical c.g. offset, combined with the rigid character of the wing, make the pitch stability much more linear and predictable than is usual for hang gliders.

We experimented with versions of the airplane that used an inboard flap as the primary pitch control device. This offers some interesting possibilities for tailless aircraft control, avoiding the non-minimum phase response characteristic of elevons. The performance advantages of a larger inboard flap were substantial, however, and flight tests suggested that the transient dynamics using elevons were acceptable, so the inboard flap was used for pitch trim and glide path control, while elevons were connected directly to the stick.

The airplane lateral dynamics were simulated using vortex lattice codes and both linear and nonlinear batch simulations. Lateral stability and control characteristics are affected by winglet incidence and cant angle as well as by the wing twist. These were studied in some analytical detail by Morris [11] and were evaluated using two radio-controlled models and test flights of several prototypes. Of particular interest for this configuration is the variation of effective dihedral and yaw stiffness with angle of attack, and the large increase in C_{np} with angle of attack that produces adverse yawing due to roll rate.

Figure 13. Radio-controlled model for S&C testing

The half-span elevons provide the large roll control moments that could not be achieved with weight shift. These surfaces, in combination with the fixed winglets produce a nicely-coupled rolling and yawing motion without the delay or performance loss associated with drag rudders or spoilers. The SWIFT's winglets are fixed surfaces, not rudders, although subsequent versions of the SWIFT have been produced with moveable rudders as well. They increase the effective span of the wing, but more importantly interact with the ailerons to produce favorable yawing moments and increase the roll control authority.

To verify the basic computed stability and trim characteristics, the first glider was mounted on a truck, and was instrumented with a load cell to measure total lift. The glider was free in pitch so that stick and elevon positions for trim could be measured. The glider was also covered with yarn tufts so that we could observe where stall first began and adjust the vortilon position if necessary. Apart from some early separation associated with large flap gaps (eliminated in the second prototype), these tests held few surprises and flight testing alone was used to verify performance and lateral handling qualities.

Figure 14. Prototype on vehicle for ground testing.

Flying the SWIFT

Eric Beckman and Brian Porter made the first flights from a 50 foot hillside in Marin County. The elevons made control on the ground very easy as the wing could be rolled easily even in the very light breezes that day. Despite the high wing loading of the first glider, take-off was not difficult and a few test glides showed that the wing was stable and controllable with a glide that was noticeably better than previous aircraft.

Flights at Mt. Tamalpais and Ft. Funston on the Northern California coast soon followed and we learned more about the glider performance and controllability. The first prototype had an excellent glide at high speeds, but with the flaps deflected at low speeds, did not do much better than good hang gliders in terms of minimum sink. Roll response was also not as snappy as the pilots desired, so we took advantage of a hard landing to retire the first wing and begin work on a second prototype. The new wing had somewhat larger control surfaces, revised airfoils, improved winglet sections, and a bit less wing area. The first flights at Ft. Funston proved that it was a big improvement.

After 10 or so hours of flying time we were quite happy with the design. It had been flown in relatively turbulent conditions, out-flew all hang gliders by a wide margin, and proved to be a pleasure to fly. But the goal was extended cross-country soaring, so the next step was to determine the wing's performance and controllability, in a true cross-country area: the Owens Valley. With a complete pilot fairing, radios and instruments, oxygen system, parachute, and water, the SWIFT took off at a gross weight of over 300 lbs from the 10,000 ft launch at Horseshoe Meadows. Hang glider pilots had begun launching at about 10 AM, but Eric waited until most others had launched; he was in the air at 11, late by Horseshoe standards. Flying north along the Sierras, he passed most of the conventional gliders. "I'm only getting to 13-5," Eric heard over the radio. "Yeah, no one seems to be getting any higher than that," said another pilot. Eric replied, "I'm at 15-5 and I haven't been circling." Just south of Bishop, Eric and the SWIFT crossed the valley to the White Mountains, passing the first of the hang gliders who had a 1 hour head start. Continuing north passed Boundary Peak, Eric began to feel hypoxic. (We later found an obstruction in the oxygen system.) He decided that he should cut the flight short because of this and began his final glide. When he reached Minas he was still at 14,000 ft and went looking for sink. Finding a bit, he lowered the flaps to act as drag producing dive brakes and landed. The first Owens Valley SWIFT flight covered about 140 miles. The idea of a true foot-launched sailplane had finally come to pass.

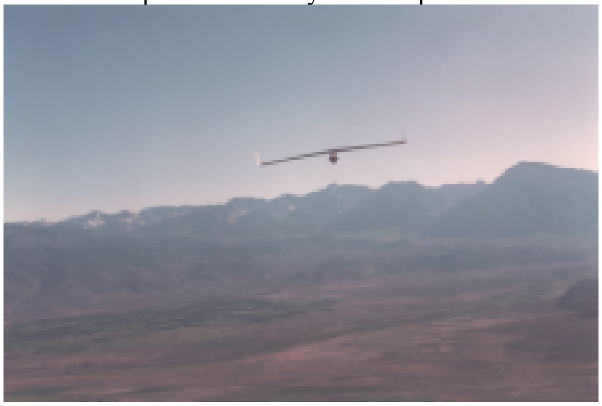

Figure 15. Prototype flies in the Owens Valley.

After these very successful prototype flights, work began at BrightStar on production tooling and soon beautiful white carbon and Kevlar SWIFTS were being produced.

Figure 15. Production SWIFT at Fort Funston.

The SWIFT was an unprecedented success in many respects. Almost doubling the performance of conventional hang gliders at the time it was introduced, it dominated several competitions and was subsequently allowed to compete only in a separate class. Many pilots have flown the SWIFT for 100-200 miles. BrightStar manufactured SWIFTs in the U.S. and granted a license to the Belgian company, Aeriane, to manufacture SWIFTs for sale in Europe. Aeriane now offers powered versions as well and even a 2-place version for training. To date about 200 gliders have been sold – not a large number by hang glider standards, but far more than many expected would be possible. There are now dealers and SWIFT schools in at least nine countries and a new generation of rigid wing hang gliders is becoming more popular.

Figure 16. Inside a 2-place SWIFT.

Conclusions and Future Directions

Although the SWIFT project has succeeded beyond most of our expectations, it did not fulfill all of our hopes. First, as a business proposition, it proved again the old rule that a good way to make a small fortune is to start with a large fortune and invest in aviation. Hand-built composite aircraft are expensive to build and despite a price significantly higher than aluminum and Dacron hang gliders, BrightStar made little money on each glider sold. More fundamentally,, the SWIFT, while providing a dramatic performance improvement over conventional hang gliders, was heavier and less convenient. Although it could be stored in a garage, it could not be thrown on top of a car with several other gliders. So, for many hang glider pilots the additional expense along with the change in social aspects of the sport were not worthwhile. The idea of foot-launching or landing at 25 mph was quite foreign to sailplane pilots and no marketing efforts were directed to this community, so it was not as widely adopted as some had hoped. The SWIFT has, however, rekindled interest in ultralight sailplanes and rigid wing hang gliders. BrightStar is currently marketing the Millennium, a version of the SWIFT that folds more compactly and costs less to produce at the expense of some performance, and several other companies are now marketing hybrid rigid wing hang gliders, cantilevered wings with flexible surfaces that can be folded. Several new ultralight sailplane designs are now flying or under construction.

With refinements in aerodynamic control and composite structures, hang gliders will continue to evolve toward more soarable foot-launched sailplanes. If one does not constrain the designs to be able to be launched like hang gliders, much higher performance ultralight sailplanes are possible. If an acceptably reliable, convenient, and quiet propulsion technology becomes more practical, a self-launching very light sailplane may finally make Lilienthal's vision of routinely soaring like birds a reality.

Acknowledgements

Much of the work described here has been accomplished by students in the Aircraft Aerodynamics and Design Group at Stanford and by Brian Robbins, Erik Beckman, and Brian Porter of BrightStar Gliders. In particular, Steve Morris, a former Ph.D. student in the design group at Stanford, was responsible for many of the analyses and studies mentioned here and is still working with BrightStar gliders to perfect the foot-launched sailplane concept.

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