THE EVOLUTION OF SAILPLANE WING DESIGN

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ABSTRACT

As the sport of soaring initially focused on exploiting ridge winds to maintain altitude, and the level of structural technology was unable to allow large spans, the low sink rates required were achieved by wings having large areas and fairly low aspect ratios. By the late 1920's, the discovery of thermals led to the use of climb/glide sequences for cross-country soaring. Thus, the trade-off between low induced drag for climb and low profile drag for cruise became a critical issue in the design of sailplane wings. Theoretical guidance for these designs was provided primarily by the lifting-line theory of Ludwig Prandtl and the minimum induced drag, elliptical loading result of Max Munk. During this time, the need for greater spans and higher aspect ratios led to structural advancements in the primarily wooden airframes and the development of some very interesting wing geometries, such as the distinctive gull wings that were then popular. The evolution of wing design through this period continued slowly until the introduction of new materials and laminar flow wing sections led to very rapid advancements beginning in the late 1950's. The use of glass-reinforced plastic structures, and later carbon-reinforced plastic, allowed designers to incorporate much larger aspect ratios than had been possible earlier. By the mid 1970's, the computational capabilities had improved to the extent that lifting-surface theories, such as vortex-lattice and panel methods, were utilized in the design process. In addition, non-linear methods were developed that could not only account for non-rigid wakes, but also optimize the wing geometry to achieve the greatest cross-country performance. These developments led to the adaptation of planforms having straight trailing edges and on to non-planar wing geometries and the, now commonplace, use of winglets. While it is not at all clear what directions wing design in the future will take, it will no doubt be influenced by technological developments such as the use of boundary-layer suction for laminar-flow control and conformable/adaptable wing geometries that "morph" to the optimum configuration for any given flight situation.

OVERVIEW

While the development of sailplane airfoils and the geometry of wings are clearly intertwined, this discussion will focus on the evolution of planar and non-planar wing planforms. As with essentially all aspects of sailplane development, that of the wing has been co-dependent and evolved simultaneously with other technologies, such as structures, materials, and, of course, airfoils. Likewise, as with the other technologies, the evolution of wing design has tracked very closely with the concurrent progress in aerodynamic theory. Nevertheless, the evolution of sailplane wing design is mostly dictated by the ever-changing mission of the sailplane. In the early days of soaring, even in light of our "seemingly" better understanding and improved methods, the wing planforms used were remarkably well suited to the glider mission and materials available at the time. This has also been true as materials have improved and the mission evolved to slope soaring, then thermal soaring, and finally to that of achieving the highest level of cross-country performance from the available weather. What the future holds is, of course, uncertain, but the recent development of ultra-light weight structures and the exploitation of so-called microlift suggests that the prospects for the future evolution of sailplane wing design will be just as interesting and exciting as has been the past.

THE EARLY YEARS

While the efforts of Da Vinci, Cayley, Montgomery, and others cannot be ignored, a natural place to begin considering the evolution of sailplane wing design is with the work of Otto Lilienthal during the last decade of the nineteenth century. Lilienthal experimented with both biplane and monoplane hang gliders and designed machines with spans ranging from 6 to 9.5 m. With areas of 8 to 13 m2, the aspect ratios were approximately 4.0, low by today's standards, but not unlike those of birds, which served as prototypes of the period.1, 2 The wing geometries and structures of the monoplane glider shown in Fig. 1 are typical of those used by Lilienthal in his designs.

The wing designs of the Wright brothers were the product of small-scale wind-tunnel tests and trial-and-error. As was the case with airfoil selection, the choice

of planform was to some extent driven by the low Reynolds numbers of their experiments, and the most efficient wings of the wind-tunnel tests benefited more from relatively greater chords than would be the case at full-scale. The sport of soaring can be said to have begun with Orville Wright's 1911 record-setting, 9 minute, 45 second, flight over the sand dunes at Kitty Hawk. The glider used for this flight, shown in Fig. 2, was typical of the Wright designs of that period.3 It was a biplane having an essentially rectangular planform. The wing had a span of 9.8 m and an aspect ratio of 6.8. The lift-to-drag ratio has been estimated to be about 5.

While the machines of this period were used for slope soaring, unlike today the goal was that of staying aloft in light winds rather than in achieving high cruising speeds. Thus, their wing loadings were low by today's standards and, in fact, more comparable to a modern hang glider. So, even though induced drag minimization was not a high priority, the benefits of distributing the wing area over a planform having a large span, along with the structural limitations of doing so, were known; however, these were understood as lowering the "end losses" such that the wing would have a high efficiency.4 Likewise, the trade-off between high aspect ratios requiring thicker airfoils and the consequential loss in airfoil efficiency due to that thickness was appreciated. It was suggested that small monoplanes have an aspect ratio around 4, while the thinner sections sufficient for an externally-braced biplane could allow aspect ratios as large as 10. The usual value was in the neighborhood of 6, with "the variation among the birds about the same."4 Because of the structural limit to increasing aspect ratios, decreasing end losses by tapering the planform and using different tip shapes was also practiced at this time. It is significant and should be noted that, Ref. 4, which documents the activities of the Cornell University student group that began in 1910, is not only an accurate record of then state-of-the-art in glider design, but it also describes the seemingly little-known, very active glider design activities and competitions that occurred between students at American universities during that time.

Most of the gliders of this time were biplanes, including the well-known designs of Chanute and Pilcher, along with most of those of the Cornell Aero Club group and many others, which were not unlike that of the 1911 Wright glider. An interesting and perhaps somewhat "ahead of its time" design, shown in Fig. 3, is the 1912 Glider No. 3 of the Cornell group. The externally braced monoplane was reported to be "very stable and efficient, although it requires a rather high speed to fly well." While the science of aerodynamics and stability and control was fairly well understood, simply flying and/or staying aloft in ridge winds were the primary goals, and the low wing loadings and relatively high-drag designs of the period reflect this.

THE BETWEEN-THE-WARS YEARS: 1920-1939

Although glider development ceased during the First World War, aeronautical development did not. When glider flying resumed after the war, primarily in Germany and driven by the prohibition on pursuing other forms of aviation, as prescribed by the Versailles Treaty, the airplane design lessons learned during the war were readily applied. This is demonstrated by the Schwartzer Teufel (Black Devil) of the Technical University of Aachen, shown in Fig. 4, which was the most advanced design to show up at the Wasserkuppe in 1920 to participate in the first Rhön meeting.5-8 The idea of this design was to combine low structural weight with the greatest possible reduction of parasite drag. Although it demonstrates a high level of technology for the time, the configuration and planform do not seem to be specialized to what is now considered suitable for a glider, but more typical of those used on a powered aircraft. The wing loading of the Schwartzer Teufel, designed by Wolfgang Klemperer, was only 9.07 kg/m2, and although the sinking speed was satisfactory, the maximum lift-to-drag ratio, estimated to be about 8 or 9, was not. While it did achieve the longest duration of the meet, the time of 2 minutes, 22 seconds, was well short of that achieved by Orville Wright a decade earlier.

By the next Rhön meeting in 1921, the Vampyr, a design from the Akaflieg (Academic Flying Group) Hannover, clearly embodied the features of a modern sailplane.5 Using the lessons of the first Rhön, the requirements for a ridge-soaring glider, which include low sinking speed, good gliding angle, sufficient strength, and good maneuverability, were clearly defined.8 The Vampyr, pictured in Fig. 5, accomplished these goals with a cantilevered high-wing and a thick, highly cambered airfoil. It made use of a single spar and, for the first time, a stressed skin D-tube leading edge to handle the torsional loads. This structure, which became typical in sailplane wings, allowed the use of higher spans and aspect ratios than had been before possible. The Vampyr, with a span of 12.6 m and a maximum lift-to-drag ratio of 16, demonstrated performance that was far superior to anything that had come before. With experience in slope soaring growing rapidly, at the 1923 Rhön meeting, the Vampyr soared for 1 hour, 6 minutes to win endurance on one flight, and flew nearly 10 km to win distance on another. It is notable that the aerodynamic benefits being demonstrated were much in line with the new lifting-line theories then being developed by Ludwig Prandtl and his students at the University of Göttingen.9-11

From this point, the formula for a successful slope-soaring glider was clear, and the "contest" for wings of the greatest spans and highest aspect ratios ensued. The series of beautiful and innovative designs from the Akaflieg Darmstadt during this period is significant.5 In particular, Darmstadt introduced the elliptical, cantilevered planform, the highly streamlined fuselage, and differentially rigged ailerons.

In 1926, Max Kegel was inadvertently sucked up into a thunderstorm, and gliders were no longer confined to the hillsides. The use of cumulus clouds as a source of lift became routine. The evolution of glider design during this period was quite steady, and its progress is well represented by the 1930 design of Alexander Lippisch, the Fafnir, shown in Fig. 6. The ability to fly cross-country shifted efforts toward gliders having higher cruising speeds and away from the design emphasis of higher-and-higher aspect ratios and very light weights. To achieve higher cruising speeds, great efforts were taken to reduce parasite drag. The fuselage of the Fafnir had a very small cross-sectional area, and with the pilot's head enclosed visibility was provided by small portholes on each side. The 19-m span wing was completely cantilevered to save drag, requiring that the root airfoil have a very high thickness ratio. The wing planform tapered to very narrow tips and, when viewed from the front, had a gentle gull dihedral distribution. While most of the early gliders had no dihedral, the handling qualities in the circling flight required for cumulus soaring benefited from some dihedral. The gull shape was perhaps copied from sea birds, known to be good in circling flight, or was perhaps to help provide much needed tip clearance with such a large span. For whatever reason, the gull-shaped dihedral distribution became the fashion in sailplane wing design for some time.

With Günther Groenhoff piloting flights of 278 km (unofficial) and 220 km (official), Fafnir became the first sailplane to fly a cross-country distance greater than 200 km.

The large spans of sailplanes during this period were only practical if highly tapered. While recognizing that an opposing view existed, Lippisch8 discouraged the use of rectangular planforms as having "static and dynamic disadvantages." He goes on to say that one could use the methods of Glauert12 to determine the best planforms from an induced drag point of view, but that there is little difference between various forms if they do not deviate too much from the elliptical lift distribution. The effect on maneuverability, however, and the importance of stall progressing from the root to retain lateral stability into the stall are noted, as is the importance of having a large aileron chord right up to the wing tip. Finally, he notes that swept and twisted wing planforms have "very pleasant" flying characteristics, and are practically spin proof. While all these points might not be fully endorsed today, it is clear that at least the most prolific sailplane designers were well versed in the most advanced aerodynamic theory of the period.

Things changed dramatically in 1930 when, while flying at the U.S. National Championships in Elmira, New York, Wolf Hirth made a thermal soaring flight under a cloudless sky. To circle as close as possible to the thermal core, along with the requirement of being able to fly fast from one thermal to the next, Hirth was the first to recognize that spans needed to be reduced for maneuverability and wing loadings increased for higher cruising speeds. He also understood the need for stability while circling, and the need for gliders to be stronger given the turbulence that could be encountered while thermalling.6, 7 In 1933, he commissioned the 20-m Moazagotal specifically for cross-country soaring using thermals. This glider was designed by Friedrich Wenk and built by the Edmund Schneider works. It is also significant in that it incorporated a disposable water ballast system to allow its wing loading to be adjusted to given lift conditions.5

In 1935, Hirth joined with Martin Schempp to set up a glider manufacturing company. As the 20-m span Moazagotal was thought to be too expensive for the expected market, the design was reworked into the Minimoa, shown in Fig. 7. The very distinctive 17-m wing of Minimoa is characterized by the classical gull shape of the period. This glider entered serial production in 1936 and over 100 were built by 1939.

Other interesting contributions to the evolution of sailplane wing design that occurred during the 1930's include the 30-m span Ku-4 Austria of 1932.3, 5 This glider, taking the idea of increased span to minimize induced drag to the practical limit, was designed specifically to fly straight for long distances under cloud streets. The Austria was the first sailplane to incorporate full-span, camber-changing cruise flaps. Also of interest was the negative dihedral built into the outer panels, the idea being to help to counter the excessive dihedral brought on by wing bending. At the opposite end of the span spectrum is the D-28 Windspiel of the Akaflieg Darmstadt. With only a 12-m span, it was built specifically for thermal soaring and had the incredibly low empty weight of only 55.5 kg. It also had full-span flaperons that could vary camber for different speeds.3, 5 The D-30 Cirrus, shown in Fig. 8, was also developed by the Akaflieg Darmstadt.5 First flown in 1938, it had a span of 30 m and an aspect ratio of 33.6, the highest employed up to that time. As a wooden structure alone was not sufficient to carry the loads for such geometry, the main spars and portions of the wing skins were of aluminum alloy. To explore the effect of dihedral on handling qualities, the D-30 was able to vary the dihedral of the outer panels from +8.5 degrees to -4.4 degrees. Also of importance during the period just before the Second World War is the DFS Meise (Olympia), shown in Fig. 9, designed in 1938 by Hans Jacob to be the "Olympic glider." It is significant in that its excellent handling qualities, good performance, and ease of construction and assembly, made it the starting point from which the post-war gliders began.5 Also unique during this period and later are the swept flying-wing sailplanes of the Horton brothers.13

THE POST-WAR YEARS: 1945-1956

Although suspended during the war years, the sport of soaring resumed soon after the end of conflict. The widespread availability of pre-war designs throughout the world and war-surplus gliders in the USA, however, did little to encourage the advancement of new sailplane designs or technologies. During this period, even though glider performance was not increasing significantly, glider costs were. To help combat this trend, a competition was held in 1956 by the Organisation Sciéntifique et Technique Internationale du Vol à Voile (OSTIV) for a simple, low-cost glider that would be limited to 15-m wingspan. The rules formulated for this competition evolved into those governing the Standard Class. The gliders that were developed for this competition, as well as most other new designs, essentially followed the course of the wooden gliders that had been established before the war. The Schleicher Ka-6, which first flew in 1955, depicted in Fig. 10, is representative of this period and, in 1958, was the first winner of the Standard Class World Championships.14 While well-known for its superb handling qualities, it was not a great departure from its pre-war predecessors.

With regard to the evolution of sailplane wing design, Bruce Carmichael's 1954 paper, "What Price Performance?" deserves recognition.15 This work represents the first comprehensive study of the influence of planform geometry on cross-country performance as it depends on thermal strength. In essence, this paper established the procedure for determining the most suitable sailplane wing geometry for given soaring conditions that has been used by sailplane designers ever since.16

COMPOSITE SAILPLANES AND HIGHER WING LOADINGS: 1957-1980

As experience with racing and cross-country soaring grew through the mid-fifties, it became evident that improved performance was to be found in the direction of increased laminar flow and higher wing loadings. In Germany, the pursuit of increased laminar flow was limited by the quality of the external surfaces that could be achieved using wooden-construction methods. This problem was addressed by Hermann Nägele, Richard Eppler and, joining later, Rudi Lindner, in the design of the Akaflieg Stuttgart FS-24 Phönix, shown in Fig. 11. The fiberglass reinforced plastic construction of this glider not only insured a surface quality that could achieve extensive laminar flow, but pioneered the method of fabrication for nearly every composite sailplane that has been built since. The measured lift-to-drag ratio of this design was found to be 40:1, and these gliders enjoyed both contest and world record successes.14 Continued refinement of this glider ultimately led to the production version, the Phoebus, and numerous other glass-reinforced plastic gliders soon followed. In the early 1970's, the Standard and Open international competition classes were joined by the flapped 15-Meter Class.

The increase in sailplane performance, primarily due to the increased amounts of laminar flow that were now achieved, was remarkable. As the primary aim of glider development at this time was focused on the use of composite materials, other than the fact that these materials allowed for somewhat greater spans than had been possible before, wing planform evolution was primarily limited to how taper breaks could best be located to approximate elliptical load distributions.17

In the USA, the problem of obtaining surfaces of high enough quality to achieve laminar flow was addressed with gliders of all-metal construction. In addition, armed with the understanding of "What Price Performance?" and driven by the strong weather conditions of the western United States, designers explored the use of ever-increasing wing loadings. Significant in this regard is the all-metal Sisu 1A, shown in Fig. 12, designed by Leonard Niemi in 1958. In 1964, flying from Odessa, Texas, Al Parker used this sailplane to complete the first soaring flight of over 1000 km.18 Also worthy of mention in the development of high-performance gliders is the HP-series sailplanes of Richard Schreder.14, 18 With a new design built and flown essentially every year for over two decades, Schreder explored the boundaries of wing loading and aspect ratio, as well as innovative methods of achieving laminar flow surfaces using all-metal structures, more than any individual before or since. Schreder was not only a prolific designer, but also an excellent pilot, and he flew his own designs to many contest successes. His most successful designs, notably the HP-11, HP-14, RS-15, and the HP-18, were produced as kits for homebuilders.

By the early 1970's, the production of metal racing gliders in the USA had given way to the composite-materials approach used in Europe. The benefits of higher wing loadings had become clear and, consequently, along with increased empty weights, wing areas became somewhat less than they had been earlier. At this point, as the gains due to increased laminar flow had essentially been achieved, researchers again became interested in other ways of increasing performance. Unique in this effort is the British Sigma of 1972, shown in Fig. 13.7, 19 This 21-m, all-metal glider used a Fowler-type flap to change the chord. In this way, it achieved an aspect ratio of 36.2 with flaps retracted for cruise and an aspect ratio of 26.8 with flaps extended for climb. Because of sealing problems with the flap system, its performance was not as great as predicted. Nevertheless, the experiment proved that the concept was viable and that, if the mechanical problems could be solved, significant performance gains were possible. Another important variable-geometry experiment was the telescoping-wing concept employed in the FS-29 of the Akaflieg Stuttgart.2, 16 While the experiment itself was somewhat successful, the idea has not been pursued further in that the glider was difficult to build and the pilot workload unacceptable.

While the performance gains due to the surface quality and strength afforded by glass fiber are remarkable, for configurations that could be regarded as more extreme, it is limited in its ability to achieve adequate stiffness. Thus, in place of glass fiber, carbon fiber was introduced. The first glider to make use of carbon fiber for the wing primary structure was the SB-10, shown in Fig. 14, of the Akaflieg Braunschweig.2, 16 For this glider, the first of the very large span Open Class "Orchids," carbon fiber was necessary in the wing center section to provide enough stiffness to allow for the 29-m span and the 36.7 aspect ratio. The SB-10, which first flew in 1972, was the first glider to achieve a glide ratio of greater than 50:1. By the mid 1970's, the use of carbon fiber was commonplace on production gliders. Not only does its superior stiffness allow for improved aerodynamics, the lighter structural weight permits a wider range of wing loadings than possible with glass fiber. Thus, carbon fiber was used to achieve adequate stiffness with minimum weight on the area-changing concept, the SB-11 of the Akaflieg Braunschweig.2, 16 The concept used on this sailplane, which first flew in 1978, was similar to that of the Sigma. In that same year, Helmut Reichmann used the SB-11 to win his third World Championship. After its initial success, in subsequent contests, it became apparent that increased area for superior climb was not the correct solution. Current thinking is to use variable geometry to reduce area for better cruise rather than increasing it to improve climb. This is because during contests a glider often must circle with others in crowded thermals, and superior climb performance that requires circling at speeds and radii that are greatly different than those of other gliders is then not possible

RECENT DEVELOPMENTS: 1981-PRESENT

Toward the end of the 1970's, the largest gains afforded by composite structures through more extensive laminar flow had been achieved and, as occurred in the 1930's with wooden gliders, researchers again looked for other means of improving sailplane performance. In the Open Class, the pursuit of ever-increasing span that began with the SB-10 continued. In 1981, the Schempp-Hirth Nimbus 3, with a span 22.9 m, and the Schleicher ASW-22, with a span of 22 m, began production.2, 16, 20 With maximum glide ratios in the mid-fifties, the performance achieved by these gliders was truly remarkable. Since then, Open-Class sailplane spans, and performances, have continued to increase. The introduction of two-seat 25-m span gliders, the Schleicher ASH-25 and the Schempp-Hirth Nimbus 3D, has had a large impact on the sport and deserves mention.2 The spans of such gliders have continued to increase, with the most recent addition being the Eta, shown in Fig. 15. This two-seat, self-launching glider has a span of 30.9 m and an aspect ratio of just over 50.16

In exploring the possibility of obtaining higher performance through alternative configurations, again as had occurred in the 1930's, designers considered the potential of flying-wing and tailless gliders. The SB-13 of the Akaflieg Braunschweig, shown in Fig. 16, is notable this regard.16 The product of a great deal of research, this Standard-Class glider first flew in 1988. While it has a number of operational difficulties, and the pilot workload is high, the SB-13 did demonstrate that it is possible for a flying wing sailplane to have performance roughly equivalent to that of a conventional Standard-Class glider. More recently, the Genesis, which entered serial production in 1994, is of importance.16 Rather than a true flying wing, the Genesis has a small all-moving horizontal tail with a very short tail arm. Although its contest success was not spectacular, like the SB-13, its performance is roughly equivalent to conventional designs, and it is reported to have excellent flying qualities.

For conventional sailplanes, the search for performance increases beyond those obtained with laminar flow caused some attention to be directed, as had been the case during the earliest days of soaring, toward determining the most suitable wing planform for a high-performance sailplane. This interest was largely stimulated through work on a shortened-span ASW-12 by Wil Schuemann that culminated in a 1983 article that argued that a wing planform having a straight trailing edge reduced spanwise pressure gradients on the surface, which thereby reduced spanwise flow and induced drag.21 In addition, it was theorized that the swept planform would reduce tip stalling and improve handling qualities. Soon after, the Schempp-Hirth Discus, shown in Fig. 17, was introduced into the Standard Class.22 This was an excellent glider, and although exactly to what extent is unclear, much of the success of the Discus was attributed to the wing planform prescribed by Schuemann. The widely used lifting-line theory of Prandtl is unable to predict any differences between different planforms having the same chord distributions, that is, a wing having an elliptical chord distribution with a straight leading edge is indistinguishable from one with a straight trailing edge.9, 10 Thus, to predict the effect of planform geometry on performance, a number of studies using lifting-surface theories, vortex-lattice as well as panel methods, were undertaken.23 Van Dam made the case that crescent-shaped wing planforms lowered the induced drag by moving the influence of the tip vortices away from the center regions of the wing24 although later, as the ability to refine the computational model of the wing increased, most of the predicted benefits disappeared. Also as computing power increased, non-linear theories were developed to account for the effects of a freely deforming wake.25, 26 After a great deal of work in this direction, however, it was found that improved planform shapes could only increase cross-country performance by, at most, a couple of percent over what had been achieved earlier.

Ultimately, the work on optimizing wing planforms, in particular considerations of the free-wake, pointed the way toward non-planar wing geometries, including those with winglets. Interestingly, the benefits of a parabolic dihedral distribution had been identified much earlier, but for practical reasons and a lack of validation was not implimented.27, 28 The benefits of winglets were explored for powered aircraft in the mid-1970's, and their use on sailplanes explored soon after.29- 31 At that time, the conclusion regarding their use on sailplanes was much the same as it was for powered aircraft; generally that winglets help the climb performance, but those gains are not sufficient to offset the penalties in cruise. Nevertheless, as understanding increased and computational analysis tools improved, it was found that winglets, such as those shown in Fig. 18, could be beneficial to overall sailplane performance.32-34 The design of non-planar wing geometries incorporating winglets has evolved to the configuration of a specially modified Discus 2 shown in Fig 19. Such geometries are found not only to improve performance through induced drag reduction, but also to benefit aileron effectiveness and handling qualities.

Another recent departure in sailplane design that deserves mention is that of the light and ultra-light glider.7, 35 Given that the evolution of sailplane performance discussed thus far has been accompanied by a comparable "evolution of cost," there have been recent efforts to blend the performance of sailplanes with the cost of hang gliders. Depending on the balance taken between performance and cost, this has resulted in a variety of new glider concepts. Gliders that were designed to the goals of the World Class, such as the PW-5 (180 kg) and the Me-7 Russia (121 kg), have empty weights that are considerably less than those typical of current Standard and Racing Class gliders (of say, 250 kg). These gliders are essentially simplified versions of the modern high-performance sailplane. Their performances are typified by maximum lift-to-drag ratios in the low thirties. A somewhat lighter class of gliders is represented by designs such as the Italian Silent, and the American LightHawk and the 11-m SparrowHawk, which is shown in Fig. 20.36 With empty weights of usually less than 100 kg, these gliders are designed for a somewhat narrower speed range than their heavier brethren. Nevertheless, they still have low sink rates and performances characterized by maximum lift-to-drag ratios in the mid-thirties. Finally, there are gliders that are closer to hang gliders, such as the Swift and the Carbon Dragon, with empty weights of roughly 65 kg.36 While often foot launchable, the performances of these aircraft, typified by maximum lift-to-drag ratios in the mid-twenties, are considerably greater than those of typical hang gliders. Gliders in this last class are being used to explore a new type of soaring, termed microlift soaring.37 Microlift is created by atmospheric discontinuities, and is usually small-scale, unorganized, and often close to the ground. Its exploitation requires specialized soaring techniques and a highly maneuverable aircraft that is capable of turning in very narrow bands of lift. Although this form of soaring is just now being explored, some very impressive flights have already been recorded.

THE FUTURE OF SAILPLANE WING DESIGN

Naturally, as with any subject, trying to predict the future evolution of sailplane wing design is difficult. For one thing, it can be influenced strongly by the interplay between the various technologies of sailplane design. Thus, the impact of materials, solar power, the digital cockpit, the movement toward self-launching, thermal detection, etc., all will have an effect on the evolution of sailplane wing design. In addition, external factors having nothing to do with any of the sailplane technologies, such as airspace restrictions, scarcity of fuels, security issues, and so forth, can have a great impact on the future direction of sailplane design. Nevertheless, by extrapolating current trends, it is possible to predict what is likely possible!

In the case of what can be termed the conventional high-performance sailplane, it is quite clear from where future performance gains must come. With regard to wings, the amount of laminar flow currently achieved on modern sailplanes by shaping alone is very near or at what the physics will allow. Thus, the attainment of additional reductions in profile drag will require some form of active control, with boundary-layer suction being the strongest candidate at the present time. If this is implemented and successful, then as is always the case, achieving the maximize performance dictates that the reduction in profile drag be balanced by a comparable reduction in induced drag. One detailed case study in how this process might play out is provided by the futuristic, fully-laminar sailplane concept developed by Werner Pfenninger.38 This 32.4-m span glider uses suction to achieve a predicted maximum lift-to-drag ratio of nearly 104. While there seem to be no technical "show stoppers" in this design, the cost of developing such a glider could be prohibitive.

Another fruitful direction in sailplane wing design extends the variable geometry concepts of the past toward a wing that, like that of a bird, can morph into whatever shape is necessary to achieve maximum performance for every flight condition. At some point in the future, this might confound the rules committees by having to examine the legality of such things as a solar-driven, flapping-wing sailplane. In any case, such a wing will require advances in materials, actuation, sensing, and control. Advances in these areas also provide the means for designs in which stability is provided not by fixed surfaces, but by small, computer-controlled, moving surfaces. In so doing, significant reductions in drag and improvements in handling qualities are possible. Of course, one question that must ultimately be addressed in the "sport" of soaring is just how much flying can the computer be permitted to do before it is no longer fun!

Because they are still so new and even the near-term direction has not yet been set, the evolution of wing design for the ultralight and light sailplanes is even more difficult to predict than it is for conventional sailplanes. In any case, one would expect new materials and methods of manufacture to have a dramatic impact on these new types of gliders. Undoubtedly, opportunities abound for yet lighter structures and higher performance. It is also likely that the "seam" between hang gliders and conventional sailplanes will become ever more blurred, and the result will be a glider that is light and convenient with very high performance. Perhaps this sailplane of the future is well represented by the Altostratus I, described by John McMasters in his 1981 article projecting forward to sailplane racing in the 21st century.39 Although the article is satirical and somewhat whimsical, the glider itself, shown in Fig. 21, is very serious and a reasonable projection of what will be technically feasible later in this century.

CONCLUDING REMARKS

Perhaps the most interesting observation in considering the evolution of sailplane wing design is the ever-present interplay between practice and theory. At least as early as 1912, the trade-off between the benefits of high aspect ratio and the loss in airfoil efficiency as it had to become thicker to handle the increased bending loads were realized, even if not fully understood. By the early twenties, it is known that Ludwig Prandtl was suggesting airfoils developed and tested at Gottingen University to glider designers, so it seems likely that results based on his lifting-line theory were being suggested as well. The assumptions required in the lifting-line theory make the theory ideally suited to glider geometries. In particular, all the chordwise information is collapsed to a single location, the so-called lifting line. For this simplification to be reasonable, it is necessary that the wings it is applied to be unswept and have reasonably high aspect ratios. This theory not only explains the origins of induced drag, but for glider-type wings, it accurately predicts its value. Thus, perhaps as early as Vampyr, the trade-off between induced drag and profile drag that has been on-going ever since, as well as the associated relationship with structures, began in earnest. Likewise, from the very beginnings with Lilienthal, the Wrights, the early American university activities and the later German ones, glider designers of the period were involved with the most advanced aerodynamic theories of the time, and, glider activities played an important role in aeronautical advances during the period up until the Second World War. During the war and after, even though the major emphasis in aeronautical research was directed toward high-speed flight and glider activities were less on the forefront, sailplane related research still contributed significantly to the advancement of low-speed aerodynamics and the use of composite structures in aircraft. This continues to this day and one would expect that future developments in sailplane technology will also have a strong interplay between theory and practice and, has been the case in the past, will come to benefit a very broad range of flight vehicles.

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REFERENCES

1Welch, Ann, The Story of Gliding, Second Edition, John Murray Ltd, London, 1980.

2Brinkman, G. and Zacher, H., Die Evolution der Segelflugzeuge, Bernard & Graefe Verlag, Bonn, 1992.

3Chen, M.K. and McMasters, J.H., From Paleoaeronautics to Altostratus - A Technical History of Soaring," AIAA Paper 81-1611, Aug. 1981.

4Wetzel, C.H., "The Theory of Glider Design," series of articles in The Sibley Journal of Engineering, Cornell University, Ithaca, NY, Nov. 1912 - May 1913.

5Simons, M., Sailplanes 1920-1945, Eqip Werbung & Verlag, GmbH, Kÿnigswinter, 2001.

6Welch, A., "Development of the Competition Glider," The Aeronautical Journal, Vol. 77, No. 756, Dec. 1973, pp. 612-619.

7Welch, A., "Evolution of the High Performance Glider," The Aeronautical Journal, Vol. 99, No. 986, June/July 1995.

8Lippisch, A., "The Development, Design and Construction of Gliders and Sailplanes," Proceedings of the Royal Aeronautical Society, No. 247, Vol. 35, July 1931, pp. 531-570.

9Prandtl, L., "Theory of Lifting Surfaces I," NACA TN 9, 1918.

10Prandtl, L., "Theory of Lifting Surfaces II," NACA TN 10, 1919.

11Munk, M.M., "The Minimum Induced Drag of Aerofoils," NACA Report 121, 1921.

12Glauert, H., The Elements of Aerofoil and Airscrew Theory, Cambridge University Press, Cambridge, 1926. Reissued in the Cambridge Science Classic Series, 1983.

13Horten, R. and Selinger, P.F., Nurflügel, H. Weishaupt Verlag, Graz, 1993.

14Simons, M., Sailplanes 1945-1965, Eqip Werbung & Verlag, GmbH, Kÿnigswinter, 2002.

15Carmichael, B.H., "What Price Performance," Soaring, Vol. 18, No. 3, May/June, 1954, pp.6-10.

16Thomas F., Fundamentals of Sailplane Design, Translated by Judah Milgram, College Park Press, Maryland, 1999.

17Holighaus, K., "The Influence of Planform and Airfoil on the Design of High Performance Sailplane Wings with Very High Aspect Ratio (Low Re-Numbers)," seminar presented at West Virginia University, Feb. 12, 1971, published in Proceedings of the 1971 Symposium on Competitive Soaring, Soaring Symposia, Cumberland, MD, 1971.

18Schweizer, P.A., Wings Like Eagles-The Story of Soaring in the United States, Smithsonian Institution Press, Washington, D.C., 1988.

19Goodhart, H.C.N., "Competition Flying in Sigma," Proceedings of the 1970 Symposium on Competitive Soaring, Soaring Symposia, Cumberland, MD, 1970.

20Selinger, P.F. Rhön-Alder. 75 Jahre Alexander Schleicher Segelflugzeugbau, R.G. Fischer Verlag, Frankfurt, 2002.

21Schuemann, W., "A New Wing Planform and Improved Low-Speed Performance," Soaring, Vol. 47, No. 2, Feb. 1983, pp. 16-26.

22Selinger, P.F., Segelflugzeuge. Vom Wolf zum Discus. Flugzeugbau bei Schempp-Hirth und Wolf Hirth 1935-1985, Motorbuch Verlag. Stuttgart, 3rd edition, 1989.

23Schlichting, H. and Truckenbrodt, E., Aerodynamics of the Airplane, translated by Heinrich J. Ramm, McGraw-Hill, Inc., New York, 1979.

24van Dam, C.P., "Induced-Drag Characteristics of Crescent-Moon-Shaped Wings," Journal of Aircraft, Vol. 24, No. 2, Feb. 1987, pp. 115-119.

25Eppler, R., "Die Entwicklung der Tragflügetheo¬rie," Z. Flugwiss. u. Weltraumforschung (ZFW), 11, 1987, pp. 133-144.

26Mortara, K.W. and Maughmer, M.D., "A Method for the Prediction of Induced Drag for Planar and Non-Planar Wings," AIAA Paper 93-3420-CP, Aug. 1993.

27Cone Jr., C.D., "The Theory of Induced Lift and Minimum Induced Drag of Non-Planar Lifting Systems," NASA Technical Report R-139, 1962.

28Cone Jr., C.D., "The Aerodynamic Design of Wings with Cambered Span Having Minimum Induced Drag," NASA Technical Report R-152, 1963.

29Whitcomb, R.T., "A Design Approach and Selected Wind-Tunnel Result at High Subsonic Speed for Wing-Tip Mounted Winglets," NASA TN D-8260, July 1976.

30Horstmann, K.H., "Ein Mehrfach-Traglinienverfahren und seine Verwendung für Entwurf und Nachrechung nichplanarer Flügelaordnungen," German Aerospace Research and Test Establishment, Institute for Design Aerodynamics, DFVLR-FB 87-51, Braunschweig. 1987.

31Dressler, U., ìAerodynamic Design of Winglets for a Standard-Class Glider,î Technical Soaring, Vol. VIII, No. 4, July 1984, pp. 118-126.

32Masak, P.C., ìDesign of Winglets for Sailplanes,î Soaring, June, 1993, pp. 21-27.

33Maughmer, M.D. and Kunz, P.J., ìSailplane Winglet Design,î Technical Soaring, Vol. XXII, No. 4, Oct. 1998, pp. 116-123.

34Maughmer, M.D., "The Design of Winglets for High-Performance Sailplanes," scheduled to appear in the Journal of Aircraft, Nov.-Dec. 2003, based on AIAA Paper 2001-2406, June 2001.

35Morelli, P., "Ultra-Light and Light Sailplanes," Technical Soaring, Vol. 22, No. 2, April 1998, pp. 47-54.

36Carmichael, B., "Ultralight and Light Sailplane Update," Sailplane Builder, Issue #3-2002, May-June 2002, pp. 13-20.

37Morelli, P., Definition of Light and Ultralight Sailplanes: For the Use of OSTIV & FAI," Sailplane Builder, Issue #5-2002, Oct.-Nov.-Dec. 2002, pp. 18-22.

38Pfenninger, W., "All Laminar Sailplanes with Low Drag Boundary Layer Suction," Technical Soaring, Vol. 11, No. 2-4, April, July, and Oct. 1987, pp.22- 44.

39McMasters, J.H., "Flying the Altostratus I," Soaring, Vol. 45, No. 2, Feb. 1981, pp 18-22.

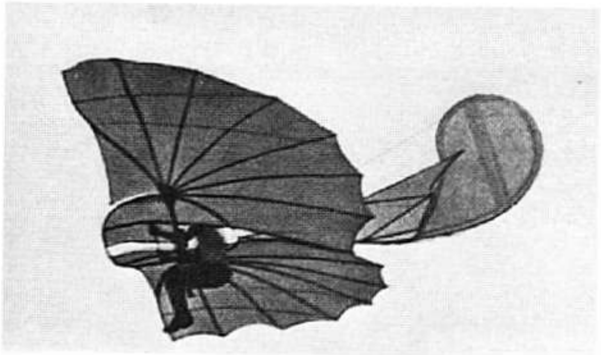

Fig. 1 Monoplane glider design of Otto Lilienthal.

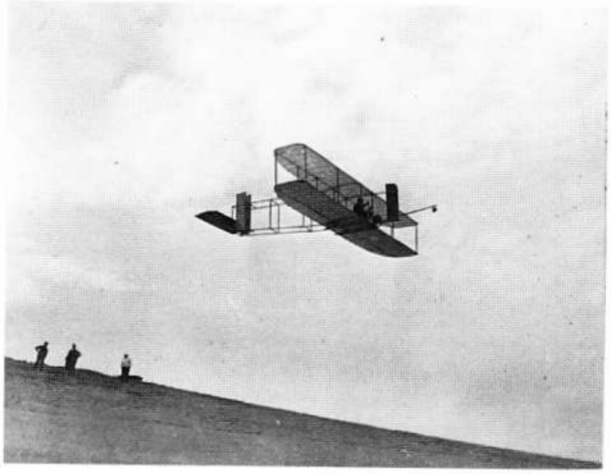

Fig. 2 The Wright glider of 1911, used by Orville to set a world duration record.

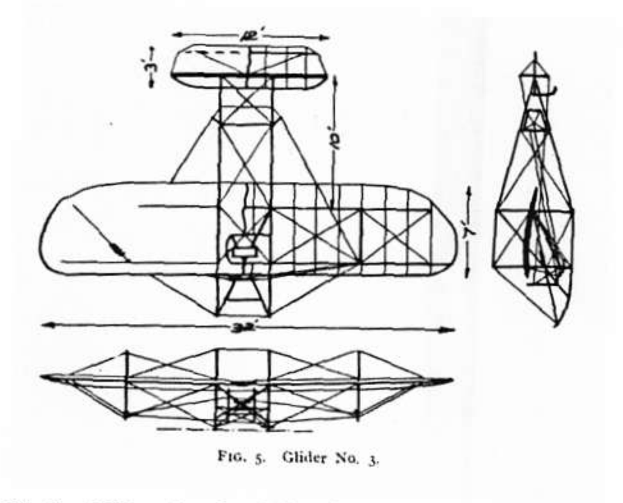

Fig.3 Glider No. 3 of the Cornell University group, 1912.

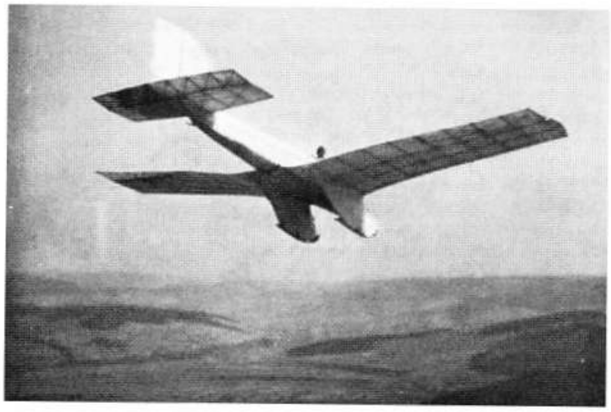

Fig. 4 The reconstructed Schwartzer Teufel of 1920, the Blauen Maus, of the Akaflieg Aachen, 1921.

Fig. 5 The Vampyr of the Akaflieg Hannover, 1921.

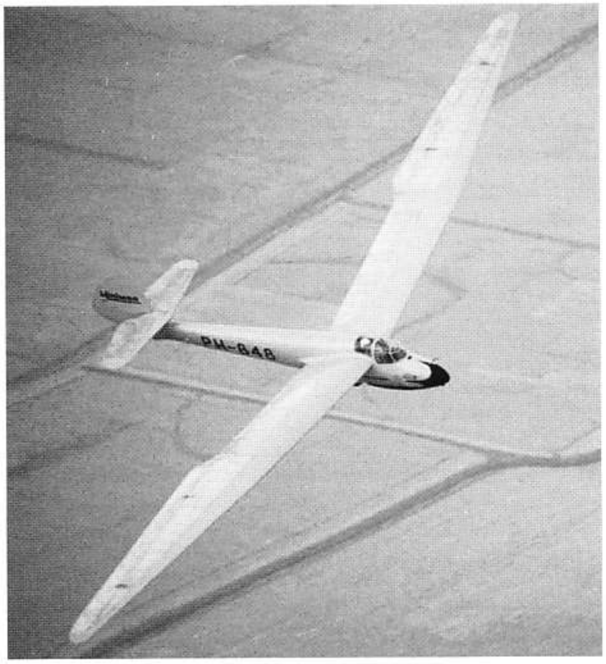

Fig. 7 The Göppingen 3, Minimoa, 1935.

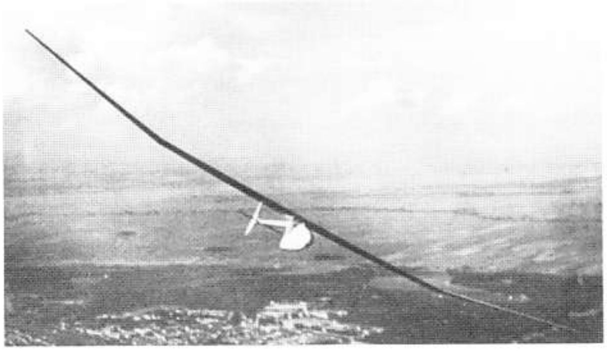

Fig. 8 The 30-meter variable dihedral D-30 Cirrus of the Akaflieg Darmstadt, 1938.

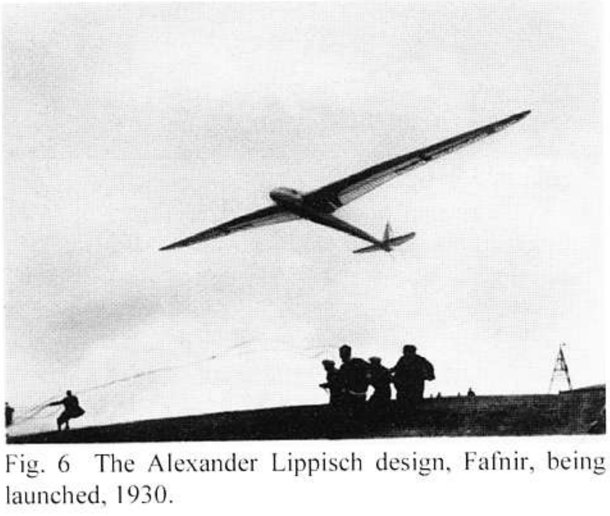

Fig. 6 The Alexander Lippisch design, Fafnir, being launched, 1930.

Fig. 9 The DFS Meise (Olympia) designed by Hans Jacobs, 1938.

Fig. 10 The Schleicher Ka-6E, designed by Rudolf Kaiser, 1965.

Fig. 11 The FS-24 Phönix of the Akaflieg Stuttgart, 1957.

Fig. 12 The Sisu 1A, designed by Leonard Niemi, 1958.

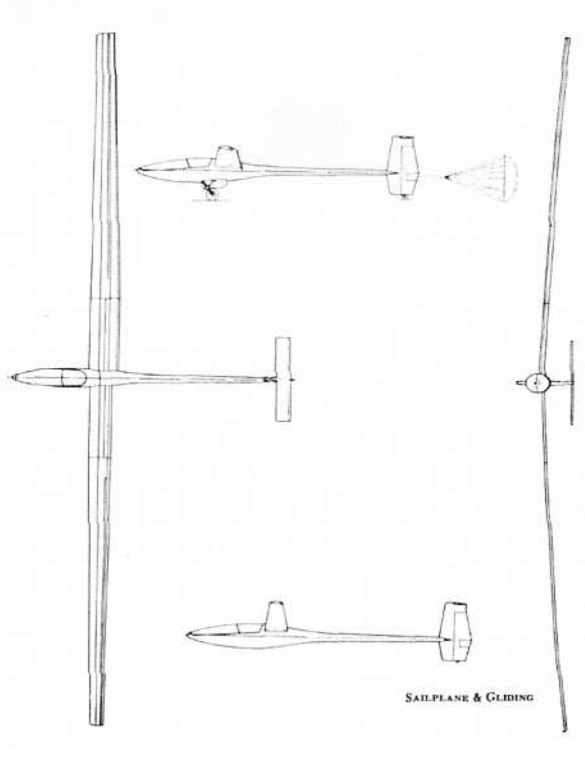

Fig. 13 The variable geometry Sigma, 1972.

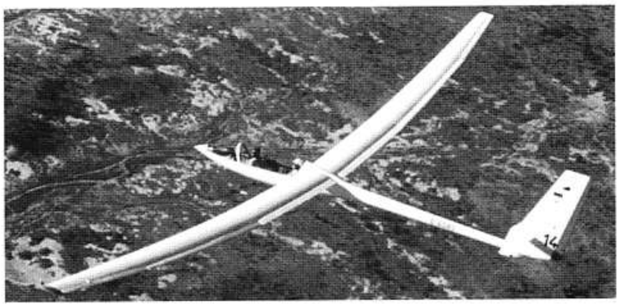

Fig. 14 The SB-10 of the Akaflieg Braunschweig, 1972.

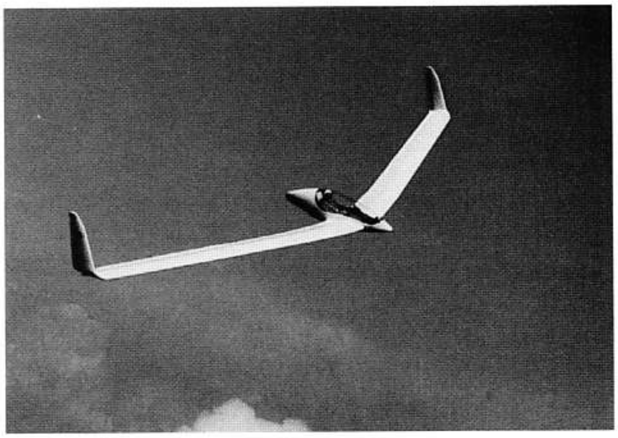

Fig. 16 The SB-13 of the Akaflieg Braunschweig, 1988.

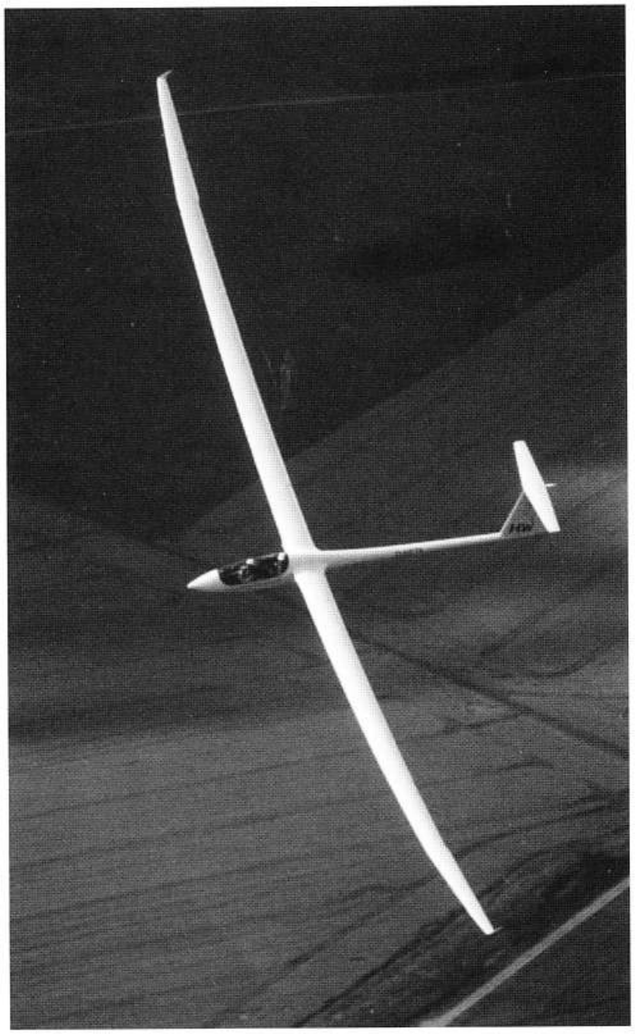

Fig. 15 The 30.9-m span Eta, 2001.

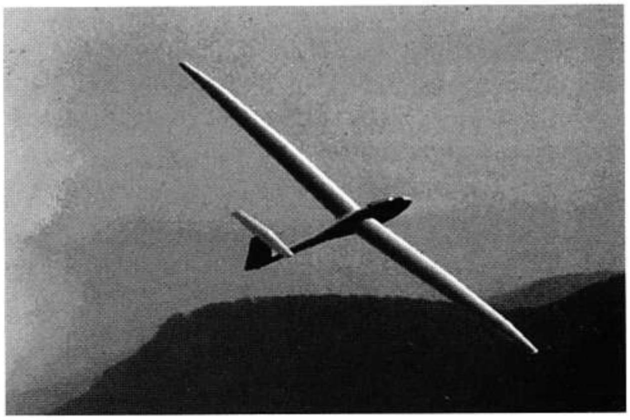

Fig. 17 The Schempp-Hirth Discus, 1984.