CONFIGURATION OPTIMIZATION OF A 13-METER-SPAN SPORT SAILPLANE

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ABSTRACT

A computerized performance analysis was used in conjunction with a parameter sweep technique to arrive at an optimum configuration for a 13-meter-span sailplane. This optimization was directed toward an aircraft which would exhibit superior low-speed performance, safe flying characteristics, and simple construction. The investigation of many combinations of wing area, taper ratio, and twist indicated that an untwisted wing with 100 sq ft of area and a taper ratio of 2.5 was a very good compromise for superior performance in both wings-level and turning flight. Further investigation of off-optimum configurations led to the proposal of a twisted, untapered planform which yielded performance within one percent of the optimum tapered wing while retaining the advantages of simplified construction and better low-speed handling.

INTRODUCTION

There is a need for a small, inexpensive sailplane with good performance. It is a fact that virtually every new sailplane designed in the past twenty years has been of a 15-meter span or longer, and given the rather limited demand for soaring aircraft, this trend is easy to understand. Individual designers as well as manufacturers have always concentrated their efforts on the most lucrative market, which has been and probably will continue to be competition sailplanes, particularly for the popular 15-meter-span standard class.

Some very beneficial results of the concentration of effort are apparent. A long list of technical advances ranging from low drag airfoils to fiberglass-reinforced plastic structures have expanded the airspeed envelope and performance capabilities of modern sailplanes to the point that maximum L/D ratios are approaching 40 for the 15-meter standard class and 50 for the unlimited-span open class.

Unfortunately, the emphasis on high-performance sailplanes intended for cross-country racing largely overlooks the needs of the majority of soaring enthusiasts. The average soaring pilot, while admiring the competition pilot's cross-country accomplishments and envying his impressive machinery, is primarily interested in staying aloft within gliding distance of the airport. The fiberglass superplane is a prohibitively expensive answer to this need. What is needed is an inexpensive aircraft designed specifically to meet the needs of the sport flyer while taking advantage of applicable technological fallout from the development of competition sailplanes.

This paper details the configuration optimization of a 13-meter sport sailplane. The ultimate goal of this study was to take advantage of aerodynamic and structural advances to produce outstanding soaring performance in a small aircraft designed for simplified construction and certification in the experimental amateur-built category.

Method of Optimization

The approach used to optimize the configuration for this design study was the time-honored parametric analysis technique, which consisted, in this case, of changing one design variable while holding the others constant and observing the trend produced in the performance of a mathematical model. The mathamatical model used was a computerized performance analysis for sailplanes developed by this author and discussed in Reference 1. The computer program, called "SAILPER", is capable of calculating performance in equilibrium gliding flight and in turns. "SAILPER" was proven sufficiently accurate for use in configuration optimization by comparing its answers with flight test data for the T-6 sailplane presented by Bikle (Ref. 2).

In addition to the capability of the mathematical model another important factor in the success of a design study are the constraints placed upon it. A study which has been constrained too narrowly may in reality be serving only to verify a preconceived notion, while on the other extreme, much valuable time can be wasted investigating unprofitable alternatives when constraints are too loose. With these pitfalls in mind, the only specific constraint applied initially was the 13-meter span limit, although other requirements, such as simple construction, safe flying qualities, and good soaring performance, implied additional (and often conflicting) constraints.

While the dominant influence of the wing on performance would focus the optimization effort almost exclusively in that area, it was necessary to provide a realistic model of the fuselage and empennage as well. The fuselage was based on one of the configurations tested by Althaus (Ref. 3) and designated shape no. 2. This basic shape was altered to an elliptical cross section (which is usual in sailplanes) with maximum height of 2.8 ft and width of 2 ft resulting in a frontal area of 4.4 sq ft. The nominal length of the fuselage was 20 ft.

Drag data was increased by a constant C_D = .01 to account for the drag of a fixed, faired landing wheel. The effect of changing the nominal tail length was simulated by increasing or decreasing the drag in proportion to the change in wetted area. Fuselage pitching moment variation with angle of attack was computed using Multhopp's method in the USAF DATCOM (Ref. 4).

The horizontal tail surface area and tail length were varied with wing area to provide a conservative tail volume coefficient of .5. A profile drag coefficient of .006 and effective aspect ratio of 5.5 were chosen as typical for this class of sailplane. The vertical tail was held constant throughout the study with an area of 9 sq ft and a profile drag of .006.

Wing parameters which could be varied were area, aspect ratio, chord distribution (taper), twist, incidence, and airfoil section. Constraining the span to 13 meters eliminated one variable because aspect ratio then became a function of wing area. A total of 5 wing area/aspect ratio combinations were investigated. These areas were 80, 100, 120, 140, and 160 sq ft, which correspond to aspect ratios of 22.74, 18.19, 15.16, 13.00, and 11.37 respectively. Each of these area/aspect ratio combinations was investigated with taper ratios (c_r/c_t) of 1, 1.5, 2, 2.5, 3, which represent a spectrum of wing shapes from a rectangular to a rather highly tapered planform. Initially, only constant linear twist rates were used.

Airfoil selection, which plays a major role in most design studies, was not accomplished by parametric analysis. The attributes of an airfoil for a sport sailplane emphasizing soaring rather than cross-country competition performance are easily determined. While good L/D is necessary, the desirability of a low minimum rate of sink makes the ratio of $C_L^{3/2}/C_D$ for the airfoil of prime importance. Additionally, if consideration is given to the requirement that a sport sailplane be able to fly slowly and efficiently while in turning flight, it is also important that the maximum value of $C_L^{3/2}/C_D$ occur at a relatively high C_L. Finally, due to the small wing chord and slow speed, the airfoil should be designed for low Reynolds number.

Fortunately, an airfoil offering outstanding compliance with these requirements was available. The FX72-MS-150A airfoil designed and tested by Prof. F.X. Wortmann (Ref. 5) had a $C_L^{3/2}/C_D$ of 210 at a C_L of approximately 1.88 and a Reynolds number of 1.0×10^6. The high camber necessary for this kind of performance, however, does create some problems. The pitching moment of the airfoil is roughly twice that of a standard sailplane section, and high speed performance suffers because of a rapid increase in C_D at the low values of C_L associated with cruising flight. Despite these disadvantages, the FX72-MS-150A section was chosen as offering the best chance for achieving a very low minimum sink rate.

Weight was held constant during the majority of the study at 530 lbs. A study of sailplane geometric data had shown that the dominant influence on empty weight was wing span, and that a 13 meter ship should weigh about 350 lbs. To this empty weight was added 180 lbs for the pilot and his equipment. The effect on performance of higher and lower gross weight was also investigated.

Center of gravity location, like weight, was held constant during most of the study at 30 percent of the mean aerodynamic chord. The effect of more forward or aft locations also received passing attention.

Optimization of the Wing Planform

The first step in the optimization was to calculate performance polars for each of the 5 area/aspect ratio combinations with each of the 5 taper ratios. These 25 configurations indicated the performance trends which would guide the remainder of the optimization.

Figure 1, which shows the effect of area/aspect ratio on rectangular wings (taper ratio = 1.0), and Figure 2, showing the same effect on wings with taper ratio of 2.5, indicate one such trend. While the smaller wings have higher wing loadings, their proportionally higher aspect ratios still provide an advantage in minimum sink performance over the larger wings. Further examination of Figure 1 shows the 100 sq ft wing to be slightly superior in minimum sink performance while the 80 sq ft wing is clearly superior at higher speeds. A similar difference in performance between the higher and lower wing loadings at high speed is also apparent in Figure 2 and there are several reasons for this trend. High loading means that the C_L required at a given speed may actually be closer to the "low drag bucket" in the C_L-vs-C_D curve for the airfoil. This can have a decided effect on performance when using a highly cambered air-

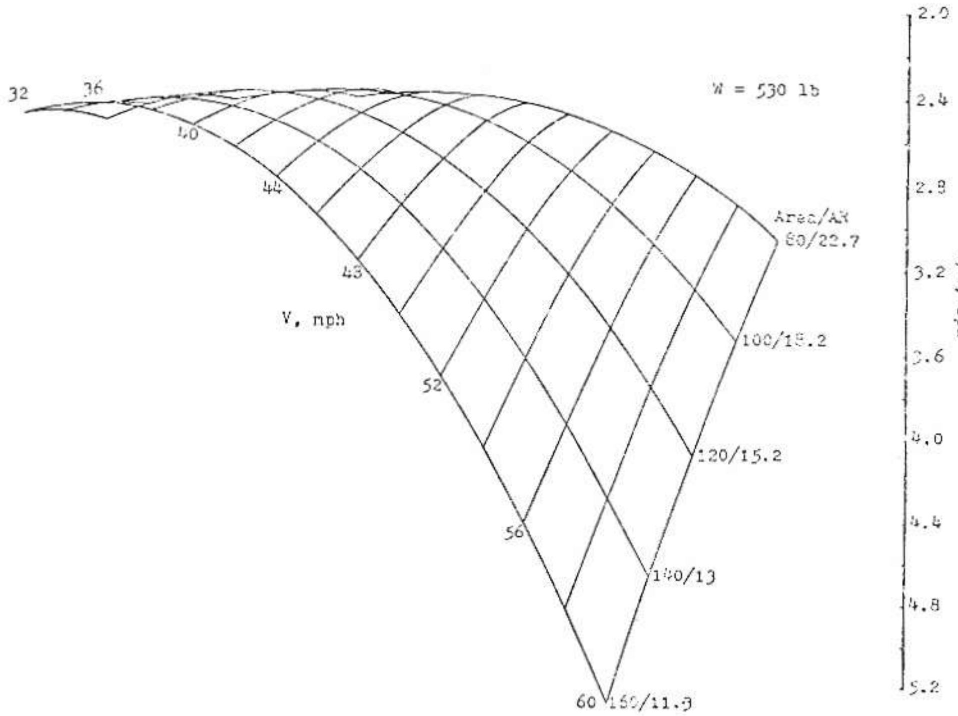

Figure 1. Effect of area/aspect ratio on untwisted rectangular wings.

foil such as the FX72-MS-150A which has a pronounced drag bucket and experiences a sharp rise in c_{d_o} below a c_ℓ of approximately .4. Of course the higher aspect ratio and the smaller wing have a favorable effect on induced drag and profile drag as well.

Despite the superior performance of the 80 sq ft wing in level flight, the higher speed at which minimum sink occurred hinted that difficulties might arise in thermaling flight. Figure 3 shows rate of sink vs turn radius plotted as solid lines for the 80, 100, and 120 sq ft wing configurations. This turn performance was obtained by running speed sweeps in turns of decreasing radius. The minimum rate of sink values at each radius were then plotted vs radius to yield the sailplane performance portion of Figure 3. In addition to the sailplane performance curves, Figure 3 also shows as dashed lines the updraft profiles (vertical velocity vs radius) for four typical thermal updraft models. Thus by noting the sailplane rate of sink relative to the updraft velocity of the desired thermal model, Figure 3 may be used to judge the climbing performance of the three wing configurations.

As anticipated, the higher wing loading of the 80 sq ft wing with its attendant higher stall speed severely limited performance in tight turns. Figure 3 shows that the larger wing areas are clearly superior when turn radius is less than 200 ft. It should also be noted that the small wing is unable to climb in the very weak, narrow thermal, which is typical of marginal soaring conditions, while the 100 and 120 sq ft wings can manage up to 1 fps climbs over a range of turn radii.

The poor turning performance of the 80 sq ft wing, and the poor cruising performance and lower L/D of the 120 sq ft wing, eliminated both of these configurations and highlighted the 100 sq ft wing as the best area/aspect ratio combination.

It is also apparent from Figures 1 and 2 that the tapered wing is superior to the untapered wing. Figure 4 shows the effect of taper on the 100 sq ft wing. The taper ratio of 2.5 seems optimum throughout the speed range. It is interesting to note that tapering the wing is of less importance at the higher speeds. This is explained by the effect of taper on induced drag. Proper ta-

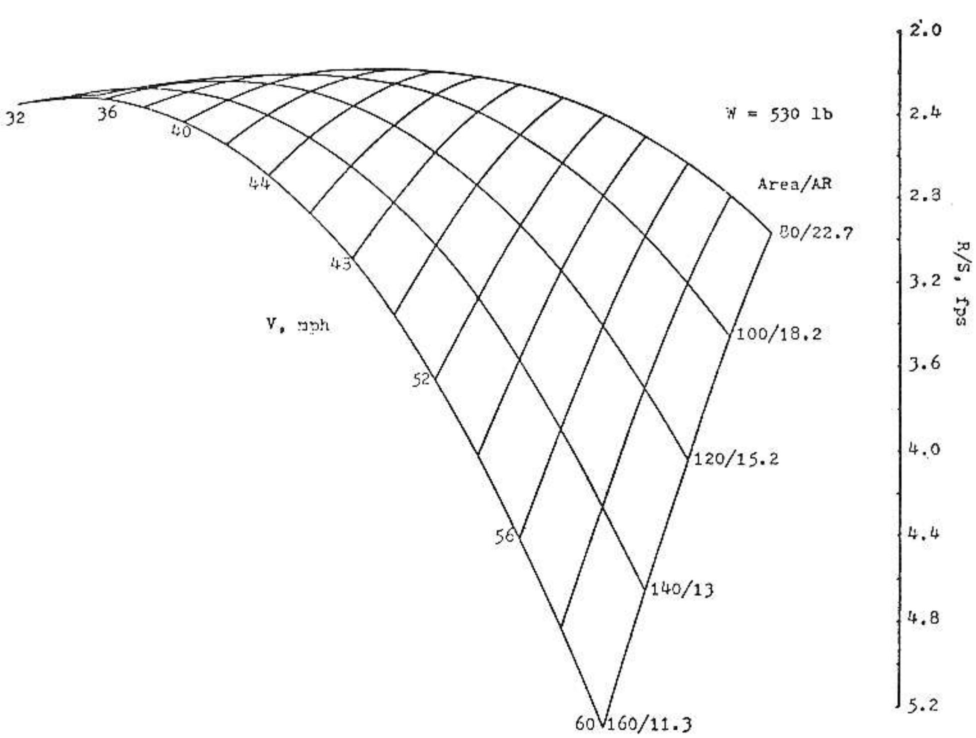

Figure 2. Effect of area/aspect ratio on untwisted tapered wings.

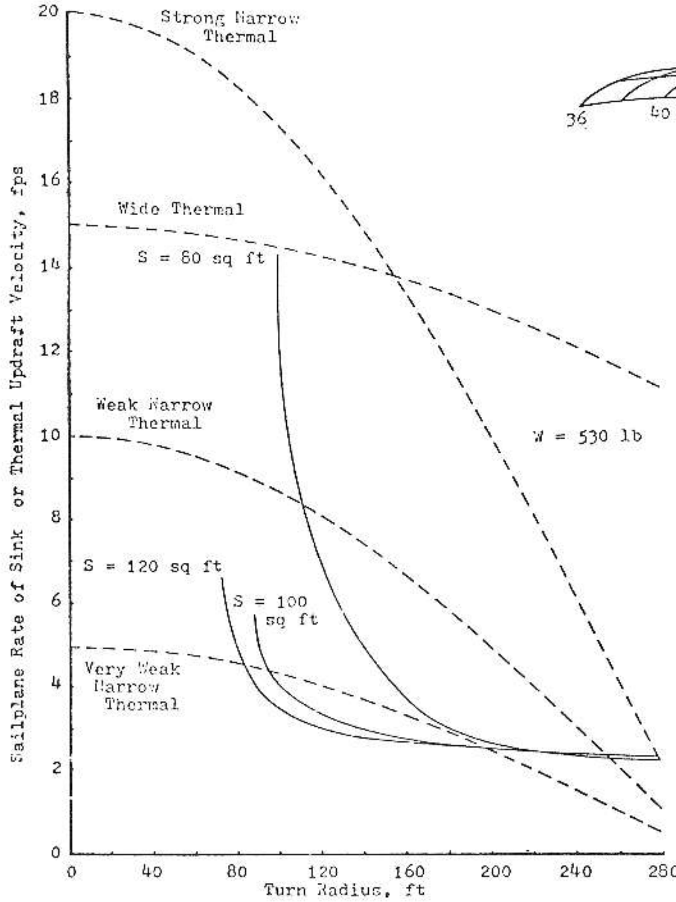

Figure 3. Rate of sink and thermal updraft velocity vs turn radius.

pering of the wing helps to lower the induced drag by more closely approaching the ideal elliptical lift distribution. At low speeds, where high C_L values make induced drag a prominent factor in performance, taper is important, while at high speeds profile drag is predominant and reducing induced drag is less noticeable. The taper ratio of 2.5 appeared to be optimum for all the area/aspect ratio combinations.

The remaining wing parameter to be investigated was twist. Reducing the geometric angle of attack of the wing sections toward the tip by twisting is intended to fine tune the lift distribution toward the ideal elliptical shape. Figure 5 shows the effect of various amounts of linear twist on the 100 sq

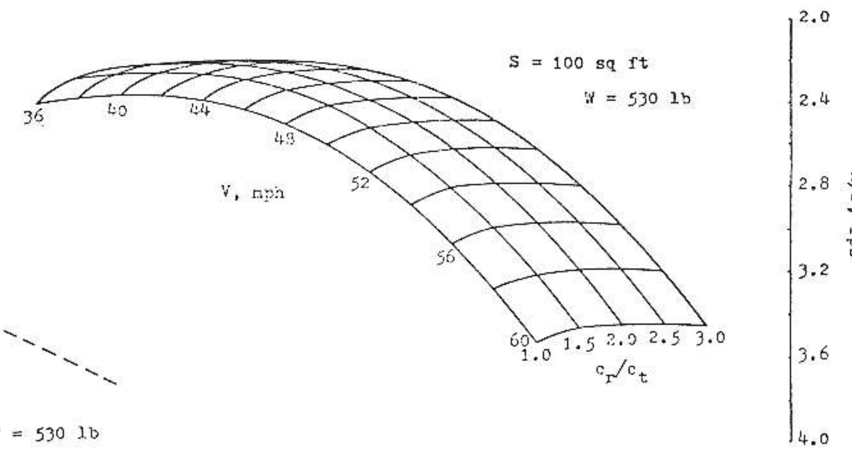

Figure 4. Effect of taper on untwisted wing.

ft wing. The trend of decreased performance with twisting was observed in all combinations of twist that were tried. Apparently the 2.5 taper ratio produces a lift distribution that is nearly elliptical with no twist and very difficult to improve. This theory was verified by calculating the spanwise efficiency of the wing from the induced drag coefficient computed by "SAILPER." The value of e for the 100 sq ft wing with 2.5 taper ratio was .97 which compares favorably with the ideal value of 1.0 for an elliptical distribution.

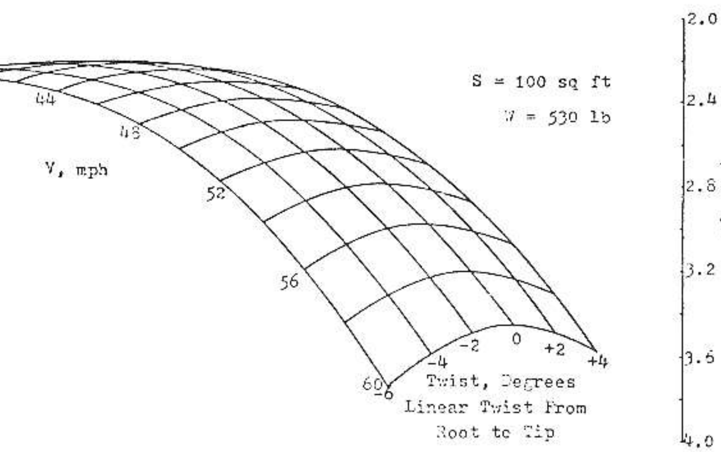

Figure 5. Effect of twist on tapered wing.

Investigation of an Off-Optimum Planform

If performance, alone, were the foremost concern in this study, the 100 sq ft, untwisted wing with taper ratio of 2.5 would probably have been the best compromise for wing configuration. However, certain other considerations prompted a second look at the untapered or rectangular planform. Rectangular wings have enjoyed very little popularity with sailplane designers because they are deficient in performance compared to the tapered planform particularly at low speeds (as demonstrated by Figure 4.) The widespread use of the rectangular wing in powered aircraft is due, primarily, to two major non-performance characteristics of that planform. First, the constant chord wing is cheaper and simpler to construct because the ribs are all identical in size and shape. Another significant advantage arises from the safer stall characteristics and superior handling qualities near stall of rectangular planforms. For these reasons an extensive study of twist was undertaken to determine if the performance of the rectangular wing could be improved to approach that of the optimum tapered wing.

As discussed earlier, twisting the tapered wing actually caused a degradation in performance because that planform already produced a nearly elliptical lift distribution.

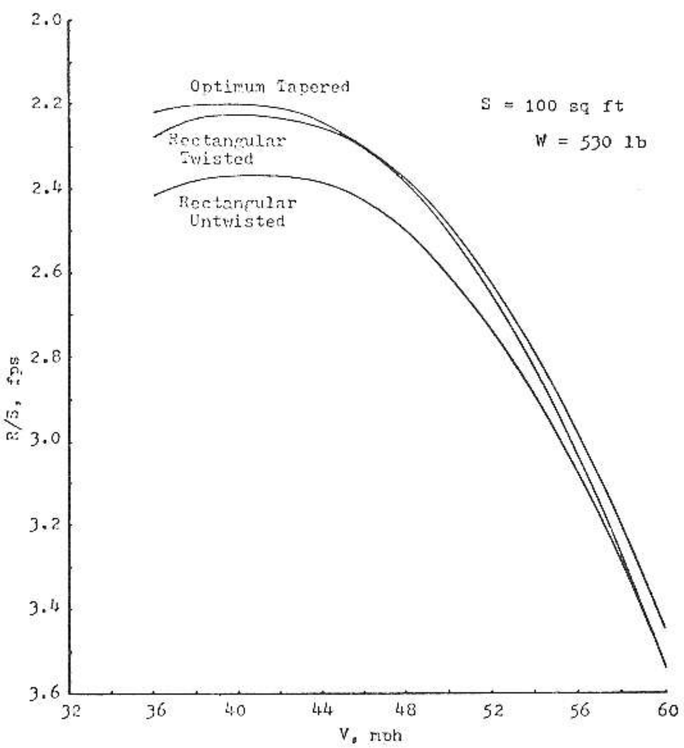

Figure 6. Comparison of rectangular and optimum tapered wings.

The rectangular wing, however, was far enough away from an elliptical distribution that some twist would be helpful. Many different combinations of twist rate were tried in an effort to find an optimum. In general, large twist rates, especially in the tip region, produced very satisfactory results in the low speed range. High speed performance, however, was most improved by smaller twist rates. There seemed to be no combination that improved both high and low speed performance. Since low speed performance was considered of prime importance, the final choice for the rectangular wing was a rather high twist of 0^{o} at the 60 percent span varying linearly to -6^{o} at the tip. Figure 6 compares the final twisted configuration with the untwisted rectangular and the optimum tapered wings. The untwisted rectangular wing is remarkably close in performance to the optimum tapered planform (less than one percent difference throughout the speed range.) Based on these results the twisted rectangular wing was chosen as the best compromise.

Before proceeding any further it seemed advisable at this point to investigate the impact of the structural inefficiency of the rectangular wing on empty weight of the aircraft. It is intuitively obvious that the rectangular wing is not as efficient structurally as the wing that is tapered in planform and thickness due to the lack of spar depth at the wing root. While a detailed weight analysis and comparison of these wings was not possible without a detailed structural layout, a 2 percent increase in wing weight was estimated using the methods of Shanley (Ref. 6). This amounted to a rather insignificant 4 lbs based on a wing weight of approximately 200 lbs.

While optimizing the wing configuration was the major focus of this design study, variations of other configuration parameters were also investigated. A sweep of tail length while holding tail volume constant showed an almost invisible improvement in minimum rate of sink and an increase of 1 in L/D ratio for a 4 ft increase in tail length.

Variation of horizontal tail volume by holding tail length constant and varying area showed only a slight improvement in performance with decreased tail volume.

Performance changes due to c.g. and weight differences were also investigated. The effect of moving the c.g. location from 25 to 35 percent of the mean aerodynamic chord resulted in a 5 percent improvement in minimum rate of sink and roughly a 2 percent improvement in L/D ratio. Figure 7 shows the effect of a variation in wing loading on the performance of the proposed configuration. As expected, the lighter loading had better low speed performance while the heavier loading excelled in high speed cruise. An interesting point brought out in this investigation of wing loading was that the L/D ratio improved by approximately .5 for an increase in wing loading of 2 psf. This was due to the increased Reynolds number at the higher maximum L/D speed of the heavier loading. This effect is, of course, invisible to most performance analysis techniques and probably small enough to be missed or ignored in flight testing.

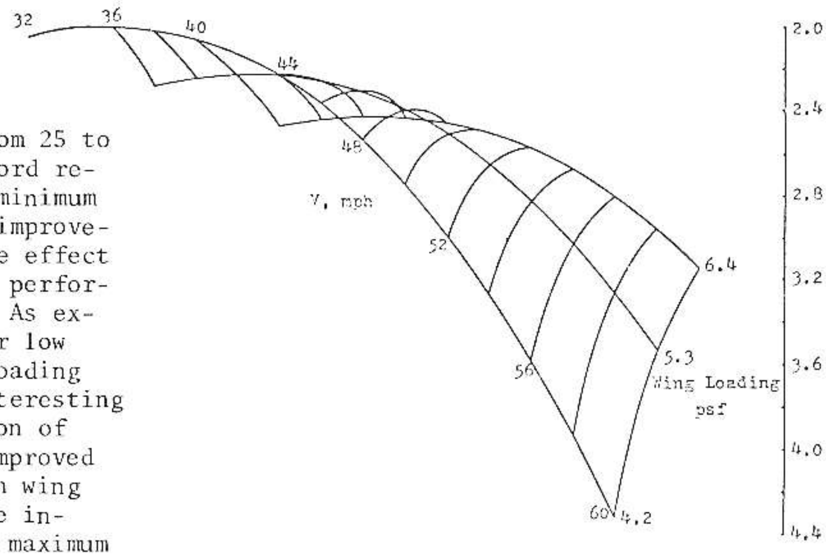

Figure 7. Effect of wing loading on proposed configuration.

Figure 8 shows turning performance of the proposed configuration at the design gross weight of 530 lbs. These data were obtained in the same fashion as that for Figure 3. The optimum tapered planform is also shown for comparison. Not surprisingly, the tapered wing with its nearly elliptical lift distribution and low induced drag shows up somewhat better at very small turn radii. However, the rectangular wing is still able to utilize the marginal lift of the very weak narrow thermal and in actual flight its superior handling at low speed might bring its performance even closer to the optimum wing.

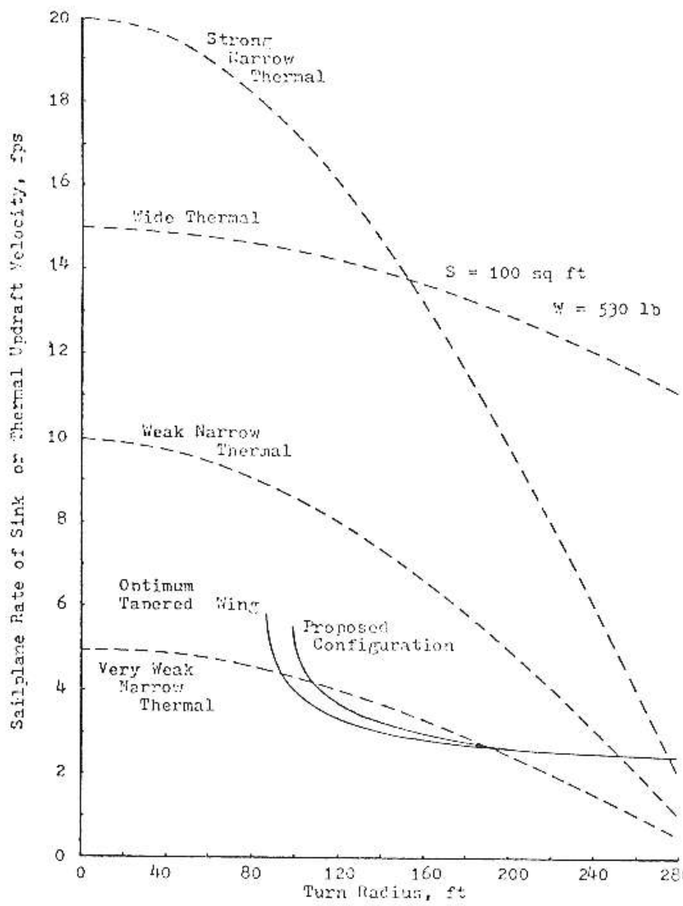

Figure 8. Rate of sink and thermal updraft velocity vs turn radius.

Figure 9 compares the calculated performance of the proposed configuration with four other sailplanes tested by Paul Bikle (Ref. 2). The Schweizer 1-26 is the most numerous single-seater in the U.S. and is a very popular sport sailplane which can also be flown in its own special one-design competition class. The Glasflugel Standard Libelle is the most numerous fiberglass standard class sailplane and has performance typical of a competitive 15-meter ship. The Schleicher ASW-12 has been flown to several world soaring records including absolute distance (over 900 mi) and is typical of the open class "super sailplane." The PS-1 is of course, the 13-meter-span sport sailplane proposed in this study.

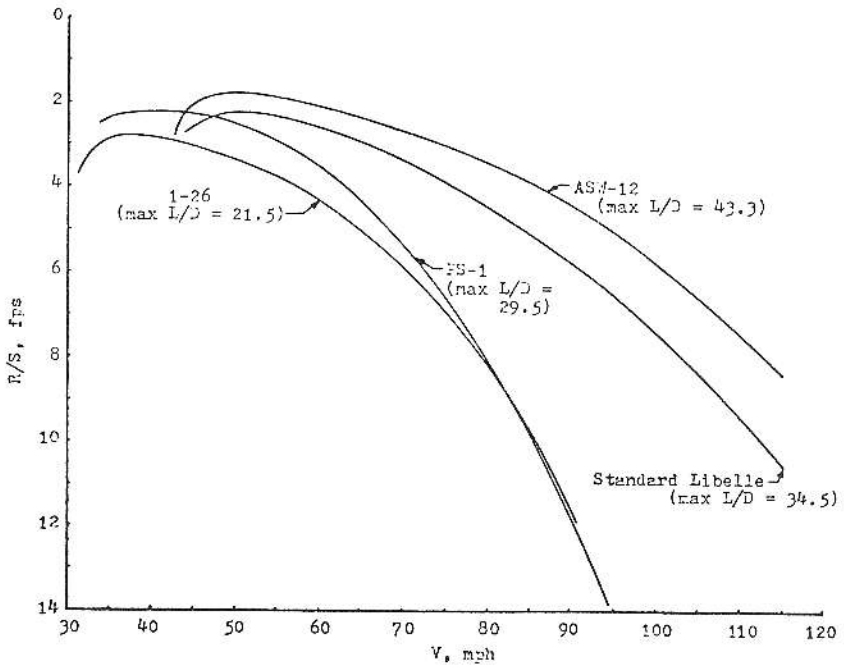

Figure 9. Performance of the PS-1 compared to three representative sailplanes.

The proposed aircraft compares very well at low speeds. It has minimum sink performance equaling the Libelle and occurring at a wider range of speeds. Its 2.23 fps minimum rate of sink occurs approximately 10 mph slower than either competition aircraft, which implies superior thermaling performance. The PS-1 also has an L/D ratio of 29.5 which is almost 40 percent better than the 1-26.

High-speed performance while certainly not spectacular is nevertheless adequate and, in fact, superior to the 1-26 up to 80 mph. It should be noted that, for sport sailplanes, speeds above 60 mph are rarely necessary.

Description of the Proposed Sailplane

Figure 10 is a 3-view drawing of the sailplane proposed as a result of this design study. The wing is rectangular with rounded, upswept tips and uses the FX72-MS-150A. The wing is twisted linearly from 0 degrees at the 60-percent span point to -6 degrees at the tip. Ailerons and flaps of 25-percent chord are shown with the spanwise break at 60 percent. Flaps are to have 90 degrees travel to allow outstanding glide path control as well as slower landing speed. Although not considered in this study because of added complexity, the high speed performance could be considerably improved by adding the capability of upward flap and aileron deflection.

The fuselage is based on shape no. 2 tested by Althaus (Ref. 3) with the cross-section modified to an ellipse and the forward section drooped for better visibility. The pilot is seated in a semi-reclining position for comfort and a smaller frontal area.

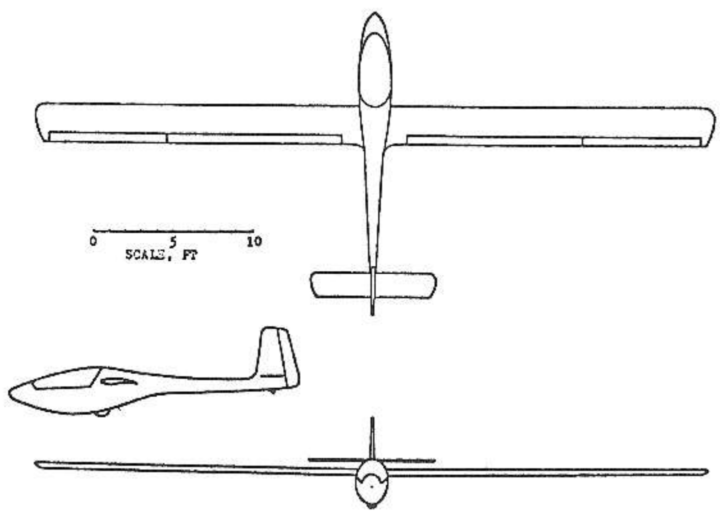

Figure 10. 3-view of the "PS-1" sport sailplane.

The main landing gear is located slightly forward of the c.g. with a small non-steerable wheel at the tail.

The horizontal stabilizer is of the all-moveable type and uses an FX71-L-150 symmetrical airfoil and employs a rudder having a nominal 30-percent chord.

The proposed structure employs a concept which has recently gained popularity with designers of home-built aircraft. This concept uses a simple primary structure of welded steel tubing or wood for strength and a secondary structure of rigid, high-density foam with a thin fiberglass skin for a good aerodynamic shape. Using this idea, the structure can be built very light and strong without being restricted to flat surfaces or simple curves. Almost any shape can be formed with the foam using simple tools and the fiberglass skin offers surfaces that are both smooth and tough.

The wing structure will consist of a wood mainspar located at approximately 35-percent chord. A plywood torque box will extend forward of the main spar to a leading-edge spar of wood. This box-beam structure will carry all bending and torsion loads. Aft of the spar thin plywood ribs will extend to a light weight spar to which the flaps and ailerons are attached. The airfoil shape will be formed with closed cell urethane foam with a skin of 1.8-oz fiberglass cloth and epoxy resin.

The empennage structure will be very similar to that of the wing except a single spar configuration is planned. If necessary to retain torsional rigidity using the single spar, the use of a heavier grade of fiberglass cloth laid up with the weave at a 45 degree angle to the span is contemplated.

The basic fuselage structure will be welded steel tubing to provide crash protection for the pilot as well as convenient hard points for attaching the wings, empennage, landing gear, and tow hook. As with the remainder of the aircraft, the external shape will be of foam and fiberglass which is well suited to forming the compound curves of the basic fuselage shape and wing fairings.

SUMMARY

Using a parameter sweep technique and a baseline fuselage/empennage model the configuration of a 13-meter-span sailplane was optimized for soaring performance.

The investigation of wing areas from 80 to 160 sq ft showed that the effect of high aspect ratio was strong enough to give the smaller areas an advantage in performance. However, when turning flight in a thermal updraft was considered, the lighter wing loadings of the larger wing allowed smaller turn radii with less deterioration of performance. A 100-sq-ft wing area and taper ratio of 2.5 appeared to be an excellent compromise for cruising and circling flight. The tapered wing had a nearly perfect elliptical lift distribution and twisting it actually degraded performance.

An effort to simplify construction led to the investigation of a rectangular planform. The untwisted rectangular wing was rather inferior to the tapered wing, particularly at low speeds where its non-optimum lift distribution caused higher induced drag.

The use of twist proved beneficial in improving the rectangular wing's performance to within one percent of the optimum tapered planform. This small difference in performance plus the superior low speed handling qualities and simpler construction of the rectangular wing prompted its choice for the proposed design.

Further studies of the effects of tail length, tail volume, c.g. location, and wing loading led to the proposal of a sailplane configuration. This aircraft, called the PS-1, appears to be a promising sport sailplane concept.

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Note:

Reference 1 consists of 91 pages of text and figures including a program listing. The development of the computer program as well as the subject matter of the preceeding paper is addressed in considerable detail. This publication may be ordered from the author at the address given below for $6.00 postage paid.

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