THE OPTIMIZATION OF WING PLANFORMS FOR LIGHT SAILPLANES

by Gary Weir

1.0 Introduction

The induced drag of a sailplane wing can be up to 80 percent of the total drag at low speeds. For this reason, it is important to minimize that induced drag, which requires large aspect ratios and a control of lift distribution along the span. That is why sailplane wings have complex planform shapes, although not all sailplanes have the same planform because of other variables such as twist and camber. The planform is usually optimized for aerodynamic efficiency, but that is not all that should be considered. The structural efficiency should also be considered, particularly if one is trying to build a light sailplane. Two factors that can be used to improve structural efficiency are forward sweep and increased taper. First let us review the optimization of aerodynamic efficiency.

2.0 Optimization of Wing Planform for Aerodynamic Efficiency

It is well known that for maximum efficiency, one should have an elliptical lift distribution along the span of the wing. However, confusion sometimes arises about that term "lift distribution". In this context the "lift" is the product of the local Cl (lift coefficient) and the local chord. Thus one may arrive at an elliptical lift distribution by employing an elliptical distribution of Cl with a constant chord or a constant Cl with an elliptical distribution of chord, or any combination in between. The elliptical chord combined with a constant Cl, as used on the Spitfire, would be ideal if efficiency were the only consideration. There is also the matter of flight safety to consider. If a constant Cl is used along the span of the wing, then the whole wing will stall at once, which certainly does not make for a very forgiving aircraft to fly. Thus it is necessary to reduce the Cl at the outer span of the wing so that the root stalls first and aerodynamic control remains at the tips, where the ailerons are. This is usually controlled with aerodynamic or geometric untwist, also known as washout. One then normally arrives at a Cl distribution which increases from tip to root. A certain minimum difference is required between the Cl's of the root and tip, probably at least 0.1.

There are also reasons for not having too large a gradient. As Alex Strojnik points out so well in Reference (1), in his discussion of rectangular wings, if there is too large a difference between root and tip Cl's, the airplane performance will suffer at low speeds. That is because the section of the wing with much larger Cl will stall long before the overall wing stalls, greatly increasing the drag. A wing with a large variation of Cl will also suffer at high speeds. The drag of a wing section rises sharply at high Cl's (low speeds) and at low Cls (high speeds). Thus at high speed, as the average Cl of the wing drops, the part of the wing with the very low Cl (typically the outer span) will experience a large drag increase. For this reason one wants to minimize the Cl variation along the span of the wing, and normally chooses the minimum variation that will insure adequate safety. It is not clear what that variation should be, but it should probably be between 0.1 and 0.2.

It is interesting to note that the Spitfire had two degrees of washout to provide safe handling, thus destroying the ideal elliptical distribution and making questionable the value of the elliptical wing. With the proper combination of taper and twist it is possible to have a safe variation of Cl along the span and to approach within a few percent of the efficiency of the ideal elliptical lift distribution. That is what each designer tries to do in choosing the wing planform and twist and camber variation. The process for the ASW-24 is well described in Reference (2) where curves of aerodynamic efficiency are plotted for wings of two and three sections of taper. That particular designer elected to stop at two sections because the gain in going to three sections was calculated to be less than one percent. The designer of the Discus, however, did choose to go with three sections, so it becomes a matter of personal preference and there is probably very little difference in efficiency between any of the better designs.

As was stated earlier, there are other factors that can effect the structural efficiency, and one of these is forward sweep.

3.0 The Effect of Forward Sweep on Wine Design

Forward sweep has the effect of increasing the loading at the root of airplane wings. It has been proposed for several fighter designs where large forward sweep (30 degrees) can provide benefits for aircraft maneuvering at large Cls. However, there are aeroelastic problems which require very careful design and probably incur a weight penalty. The amount of sweep used in gliders is far less and should not incur these problems. In gliders, forward sweep is seen most often in two place aircraft such as the Blanik where it is used to put the second passenger seat closer to the c. g. (centre of gravity) and thus limit the c. g. travel with a

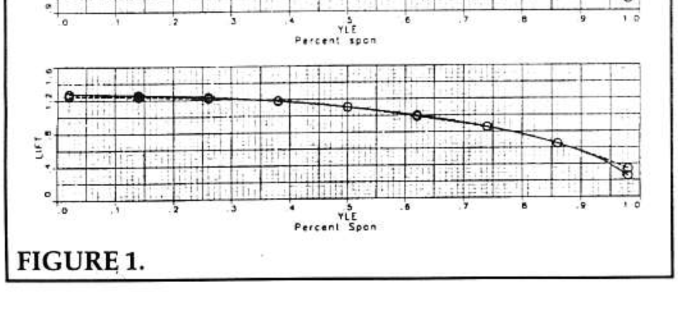


FIGURE 1.

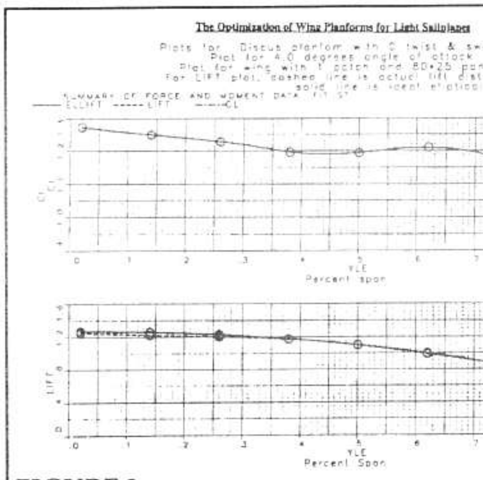


FIGURE 2.

second person. It is also seen on some very light sailplanes such as the Russia, where it is again used to limit the movement of the c. g., as the pilot might well weigh more than the aircraft. The Genesis is about the only heavy single place sailplane that employs significant forward sweep. It is not clear why forward sweep is not used more often, as it should be possible to limit the c. g. travel and thus reduce the trim drag variation with pilot weight.

In order to further define the effect of forward sweep, a model of the Discus wing was constructed and analyzed using a panel code as described in Reference (3). As the amount of twist and the camber variation were not known, this does not represent an exact analysis of the Discus wing, but rather provides a convenient comparison for analyzing other designs. Figure 1 gives the lift distribution of the base wing with an assumed washout of 1.0 degrees at the tip. Figure 2 gives the lift distribution of the same wing with no washout but with 5 degrees of forward sweep. It can be seen that the lift distribution is nearly the same . Thus the effect of the forward sweep is to move the loading inboard enough so that the washout can be reduced. At a constant Cl there is no benefit because the lift distribution remains the same.

4.0 The Effect of Wing Taper

4.1 The Effect of Singly Tapered Planforms

The other major structural parameter that needs to be investigated is the amount of taper in the planform from root to tip. High taper (large root chord) is desirable because it allows a deeper, and therefore lighter, spar. High taper also tends to increase the roll response of the aircraft.

In order to investigate the effects of taper and sweep, a systematic study was done of a singly tapered wing (with a linear variation of chord from root to tip) of 15 meters span and an aspect ratio of 20. The taper ratio (ratio of tip chord to root chord) was varied from 1.0 to 0.3, the forward sweep was varied from 0 to 10 degrees, and the washout was varied from 0 to 2 degrees. The reference wing was that of the Discus model. Because the efficiency varies with Cl, a series of runs was made with the Discus wing model at different Cl to obtain the variation in aerodynamic effi-

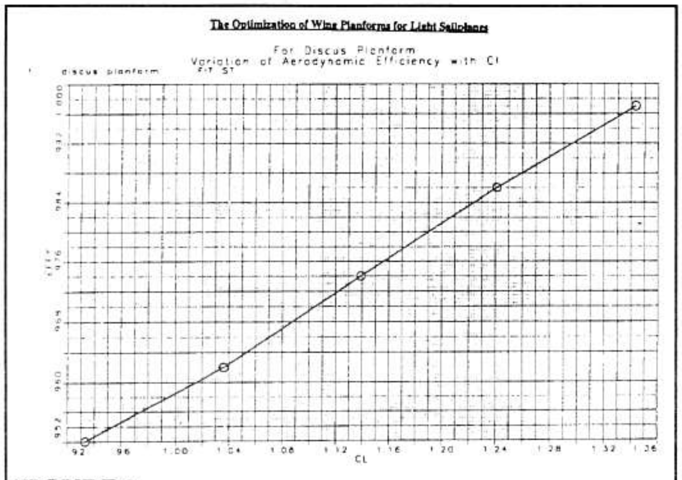


FIGURE 3.

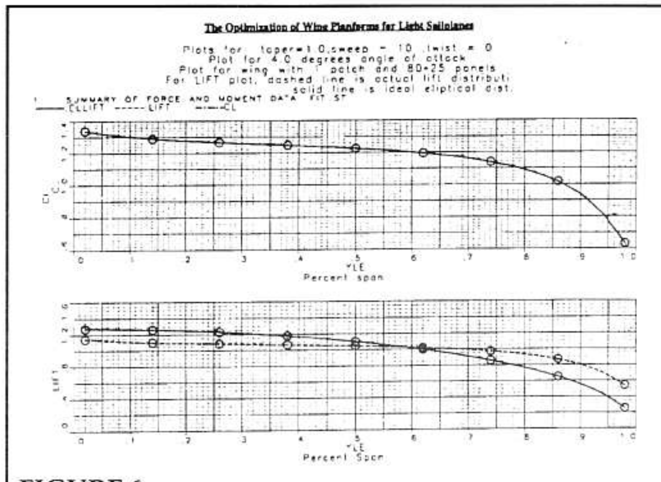


FIGURE 6.

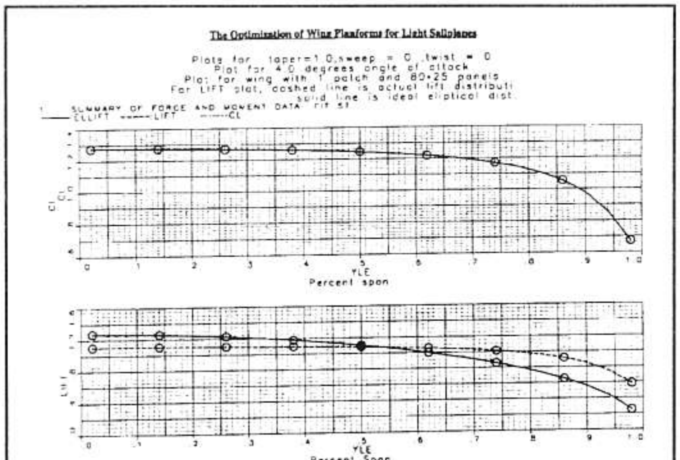
ciency shown in Figure 3. The panel method analysis gives the actual induced drag, while the ideal induced drag can be calculated from the formula

Cdi = Cl**2/(3. 14*AR)

where AR is the aspect ratio. From this the aerodynamic efficiency can be calculated as the ratio of the ideal induced drag to the actual induced drag. In the present study, the calculated efficiency of each configuration was compared to the Discus values from Figure 3 at the same Cl, to obtain an efficiency debit

Let us start by examining the results from the first case with a taper ratio of 1.0 (rectangular wing) zero sweep and zero washout, given in Figure 4. In the upper part of the figure the Cl distribution is given while in the lower part the lift distribution is given and compared to the ideal elliptical lift distribution. It can be seen that the lift distribution does not agree at all well with the ideal, with a subsequent penalty in efficiency. The efficiency for this configuration is 86 percent, which is actually good for a rectangular wing, because of the large aspect ratio. However it is 11 percent short of what the Discus planform can deliver and that difference cannot be given up in a sailplane in which performance is paramount. From the given lift distribution, one could guess that this layout should benefit from washout and Figure 5 is a plot of the results for the same planform with 2 degrees of washout. Indeed the efficiency has risen by 3 points and there is a greater (safer) variation of Cl along the span. Greater washout would increase the efficiency but also increase the variation of Cl along the span, with the consequent problems that were previously mentioned .

Just as washout improved the situation by removing



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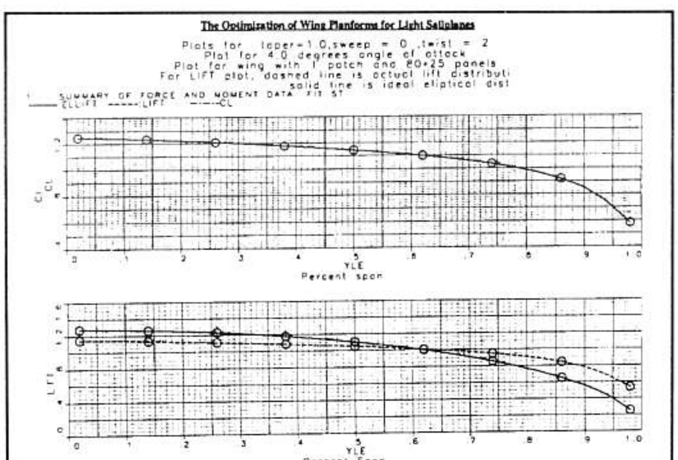

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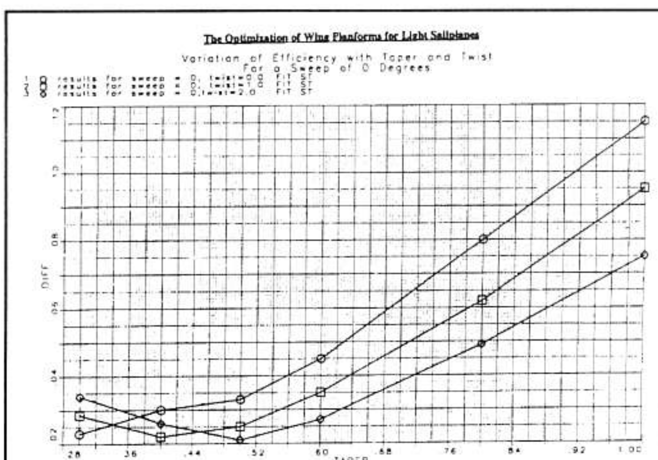
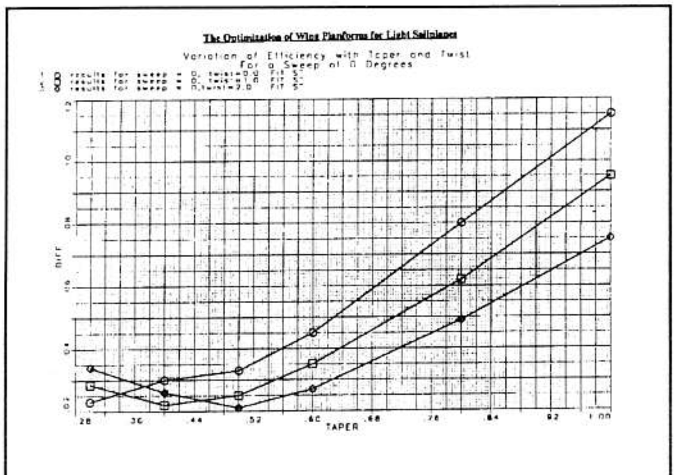


FIGURE 7.



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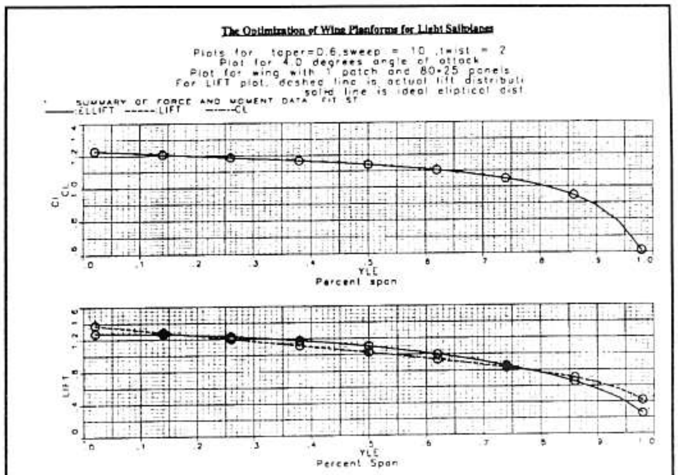

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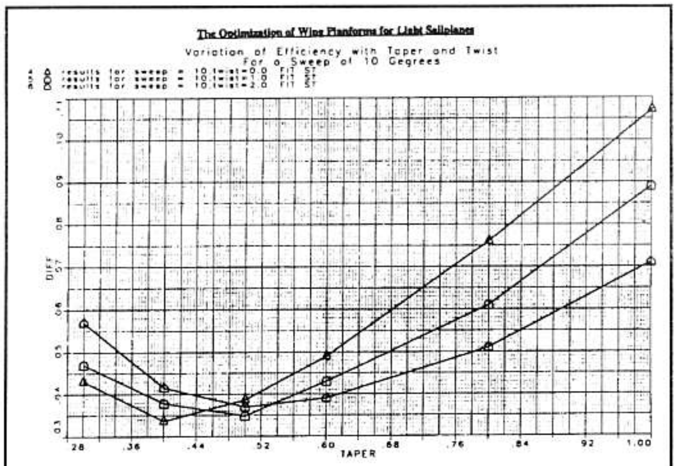

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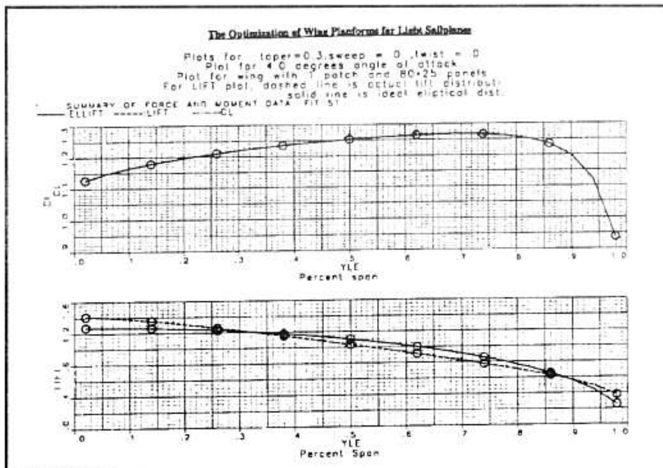


FIGURE 11.

loading from the tip, forward sweep should also improve the situation by increasing the loading at the root. Figure 6 is a plot for the same planform with no washout and 10 degrees of forward sweep. Again there is an improvement in efficiency but this time it is only 1 percent.

It is not possible to present all of the results here so they are summarized in Figures 7 and 8 which give the delta efficiency down from the reference Discus planform The rectangular wing result with no twist or sweep is shown as the right uppermost point in Figure 7, showing an 11.5 percent debit in efficiency compared with the reference case. Note that the best efficiencies occur at taper ratios between 0.4 and 0.5, and are within 2-3 percent of the reference case, which is quite good. But one has to look at the Cl distribution to see if it is sensible. Let us look for instance at the one with the best efficiency (with a taper

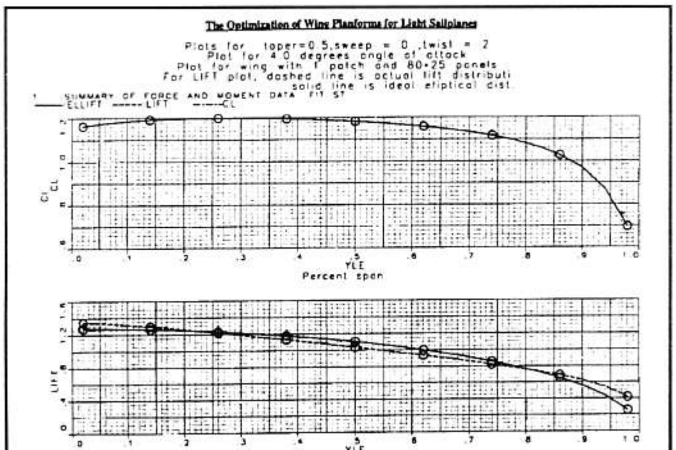
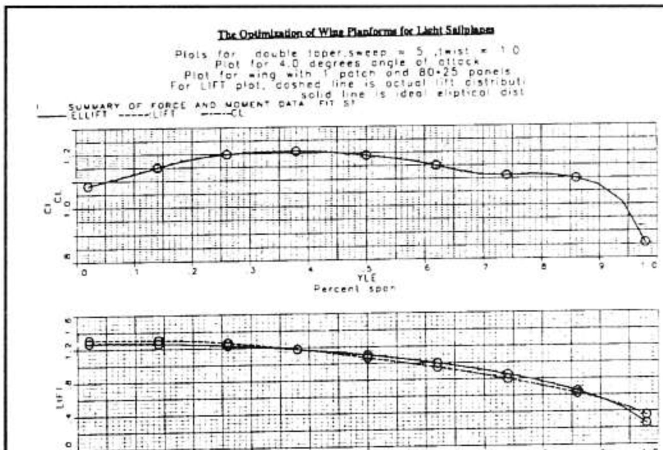


FIGURE 9.



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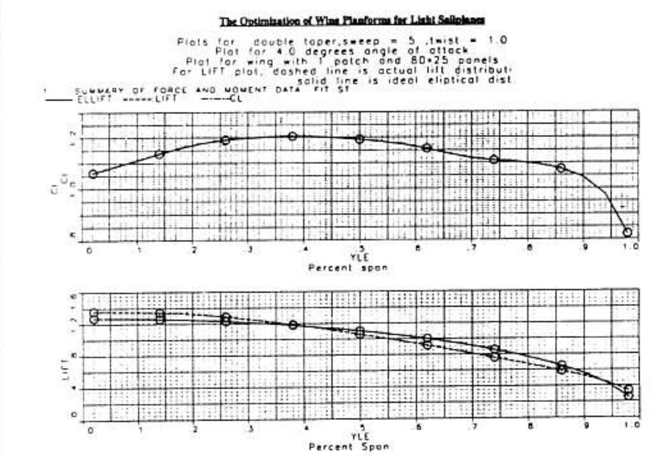

FIGURE 13.

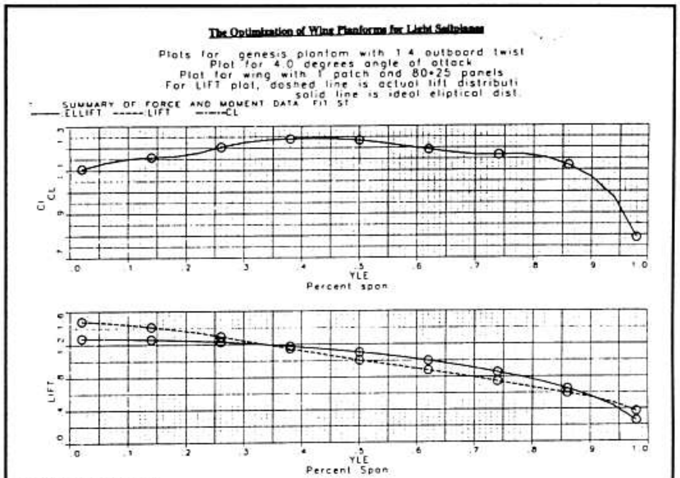

FIGURE 15.

ratio of 0.5, sweep of 0 degrees, and twist of 2 degrees) with the results given in Figure 9 . The Cl distribution is not very satisfactory as it is almost constant over 60 percent of the span. A better overall result would be that shown in Figure 10 for a taper ratio of 0.6, forward sweep of 10 degrees, and twist of 2 degrees. Here there is a very good distribution of Cl but the efficiency has dropped to 4.0 points below the reference value. In order to make further improvements, double tapered planforms were examined. Before leaving the single tapered results, however, let us look at the results in Figure 11 for a taper ratio of 0.3, sweep of 0 degrees, and twist of 0 degrees. Here the efficiency is again quite good (a debit of 2.3 percent) but the Cl distribution is quite poor. The effect of the very high taper is to push the max Cl out towards the wingtips, which is the very worst position for safe handling. With a taper ratio of 0.6, the root chord is 35.0 inches (compared to 32.0 inches for the Discus) and the tip chord is 21.0 inches.

4.2 The Effect of Double Tapered Planforms

For the purposes of this study, it was assumed that the break in taper ratio was at 70 percent span (approximately where the aileron begins) and the tip chord was fixed at 12.0 inches. Reynolds number considerations suggest that it should not be less, while minimizing the tip chord maximizes the root chord. With the tip chord given, the break point fixed at 70 percent span, and the average chord given (28.0 inches as or. the Discus) the choice of root chord determines the entire chord distribution along the span

Root chords were varied from 32 to 48 inches. Besides varying the root chord, the sweep and twist were also varied Rather than perform a systematic variation of all of the parameters, at each value of root chord, the sweep and twist were varied to try and produce the best overall results. The amount of forward sweep was limited to 5 degrees because larger amounts put the wingtip in front of the pilot's head. Let us look at the results for several values of root chord

The results in Figure 12 are for a root chord of 38 inches . They are for a sweep of 5 degrees, a twist of 1 degree in the outer part of the wing, and a twist of 2 degrees in the inner part of the wing, each measured relative to the baseline airfoil. The washout at the tip is to provide a suitable falloff in Cl from the peak to the tip at some sacrifice in efficiency. The washout at the root is to reduce the lift closer to the ideal elliptical value, increasing the efficiency. The lift distribution, peaking at 40 percent span, seemed wrong initially, but on reflection, there might actually be an advantage The distribution arises because the large taper

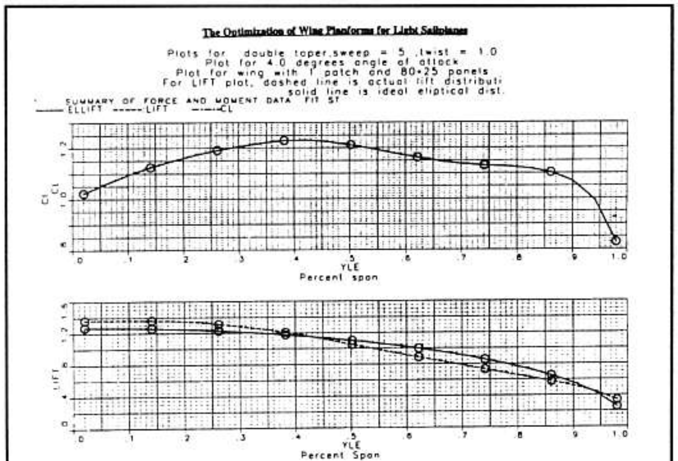

FIGURE 14.

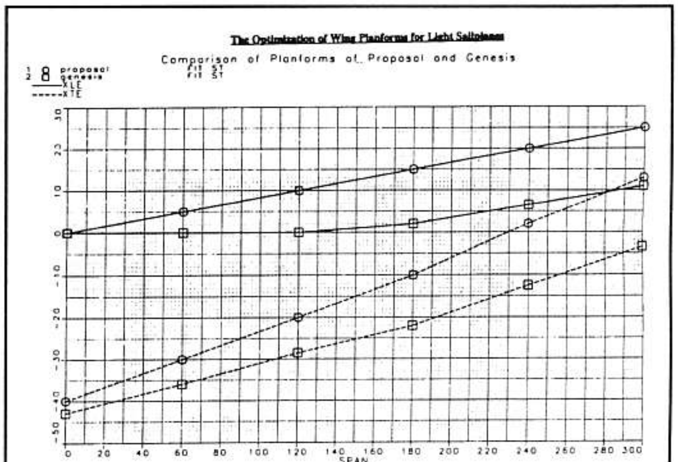

FIGURE 16.

ratios tend to drive the peak loading towards the tip, while sweep tends to drive the peak loading towards the root. Combining the two gives peak loading in the middle of the span. As the wing approaches stall, the root section will normally have the highest Cl and therefore stall first, before the wing stalls. The problem with this is that as the root section stalls, the flow over the rear fuselage and tail section will be disrupted, greatly increasing the drag. This is also the source of the buffeting that one experiences as the aircraft approaches stall. With the lift distribution shown in Figure 12 the drag may not rise so steeply as the aircraft flies at minimum sink (typically very close to stall). The aerodynamic efficiency for this planform is 95.9 percent compared with 97.2 percent for the Discus planform.

The results in Figure 13 are for a root chord of 40 inches. The efficiency for this layout is 95.6 percent, only 0.3 percent worse than for the previous case. The only drawback is that the variation in Cl from the peak value to the root is starting to increase.

The results in Figure 14 are for a root chord of 42 inches. Here the efficiency has dropped to 94.5 percent and the Cl variation from max to root has become excessive. Larger root chords were tried but the results were completely unsatisfactory.

Out of curiosity, an analysis was done of the Genesis planform, using the Discus airfoil for all spanwise positions and assuming a washout of 2 degrees for the tip and root of the wing. The efficiency is calculated to be 95.1 percent. Note that this does not reflect the performance of the actual Genesis wing, but is merely an analysis of the effect of using its planform shape. Note the similarity of the results of Figure 15 and Figure 14 and the similarity of the planforms, as shown in Figure 16 . The chord distribution is very similar; the difference is mainly in the amount of sweep.

Let us take the case with a root chord of 40 inches as being the optimum as the efficiency is only 1.6 percent worse than that of the Discus while the root chord is 25 percent greater. If one were additionally to choose a greater thickness ratio for the root section, (17 percent instead of 13 or 14 percent), one could easily arrive at a spar depth 50 percent greater than the Discus at the root. This would have very considerable effect on the wing weight at a given load factor. And since the wings typically represent half of the plane weight, the aircraft weight could be reduced significantly.

5.0 Conclusions

It has been shown that forward sweep and high taper ratios can be combined to give a wing planform that is only slightly less efficient than one optimized for aerodynamic efficiency, but which can be much more structurally efficient.

References

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