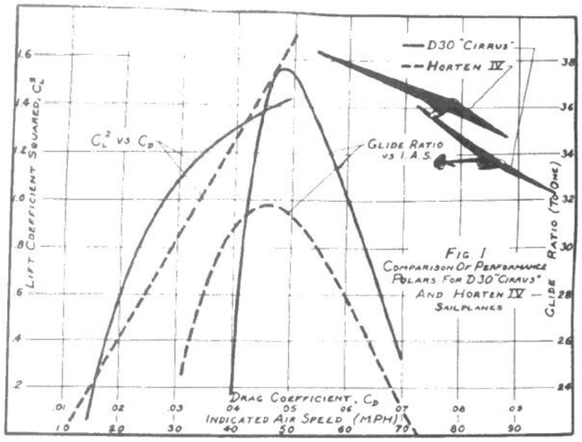


Fig. 1
Comparison of Performance Polars for D30 "Cirrus" and Horten IV Sailplanes

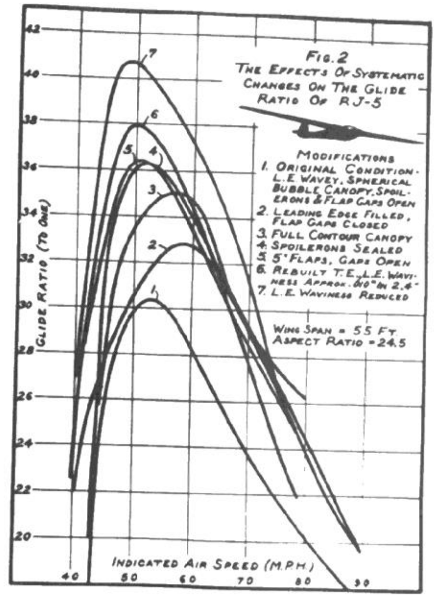
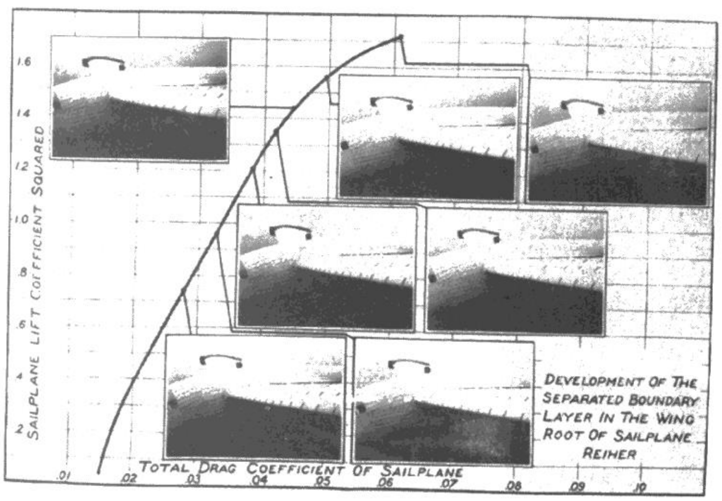


Fig. 2
The Effects of Systematic Changes on the Glide Ratio of RJ-5



Development of the Separated Boundary Layer in the Wing Root of Sailplane Reiher

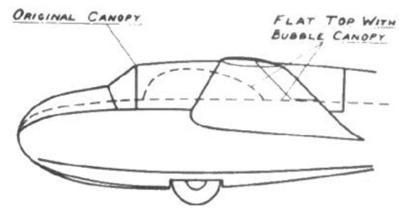


Fig. 4
Flat Top Method for Reducing Wing Root Separation

CONTROL OF THE BOUNDARY LAYER ON SAILPLANES.

By August RASPET.

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INTRODUCTION.

The great progress which has been made in aeronautics is due to a large measure to the facts obtained from windtunnel measurements. In sailplane development, however, only a very few machines have been tested in the windtunnel. Of those that have been so tested, there are the Weihe 1) and the Orlik 2). In the windtunnel the maximum glide ratio found for the Weihe was 21.8 at a test Reynolds number of 350.000. Free flight measurements, on the other hand, show the Weihe to be capable of a maximum glide ratio of 31.2.

Because the sailplane designer cannot depend on windtunnel results, it becomes necessary for him to control his development of the high performance sailplane by means of full scale flight tests. A most elegant series of sailplane flight performance measurements is that of Spilger 3). Having available free flight test data of many sailplanes, one must analyze the results in order to differentiate the effects of individual aerodynamic parameters.

One of the most powerful analytic techniques with which to treat flight test data is based on the Oswald 4) airplane efficiency factor, e,

$$C_D = C_{Dpe} + \frac{C_L^2}{e \pi A R}$$

where AR is the aspect ratio and C_{Dpe} is the effective parasite drag coefficient. It is easily seen that a plot of C_L^2 versus C_D will yield a straight line over the region of the polar where the above relation holds. To compare sailplanes whose polar is linear in $C_L{}^2$ vs C_D, therefore, it is merely necessary to know e and C_{Dpe}. In Fig. 1 is shown a comparison of the D-30 Cirrus and the Horten IV. The polars were computed from data obtained from Zacher 5). The drag of the Horten is lower only at lift coefficients below 0.5. The steeper slope of the D-30 is due to its higher effective aspect ratio. Efficiency factors are 81% for the D-30 and 63% for the Horten. C_{Dpe} for the two sailplanes is 0.014 and 0.010 respectively.

This paper will be devoted to an exposition of aerodynamic concepts leading to sailplane performance improvement. These concepts have proven to be a very powerful tool for maximizing the performance of every sailplane to which they have so far been applied 6).

From the Oswald performance equation one sees that the aim in systematic performance maximization of a sailplane is to raise the efficiency factor and reduce the effective parasite drag coefficient. An example of the results of this process is illustrated in Fig. 2, which shows the systematic improvement of the sailplane RJ-5.

Having analyzed a sailplane by means of a flight measurement and a linearized polar, $C_L^2 = F(C_D)$, one must next diagnose the ills of that sailplane and attempt in some rational

1) See reference 1 on page 32
2) See reference 2 on page 32
3) See reference 3 on page 32
4) See reference 4 on page 32
5) See reference 5 on page 32
6) See references 6, 7 and 8 on page 32

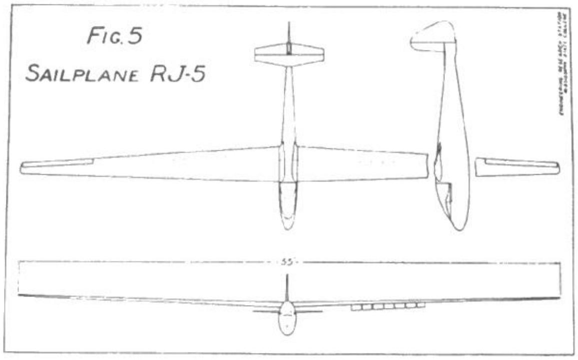


FIG. 5
SAILPLANE RJ-5

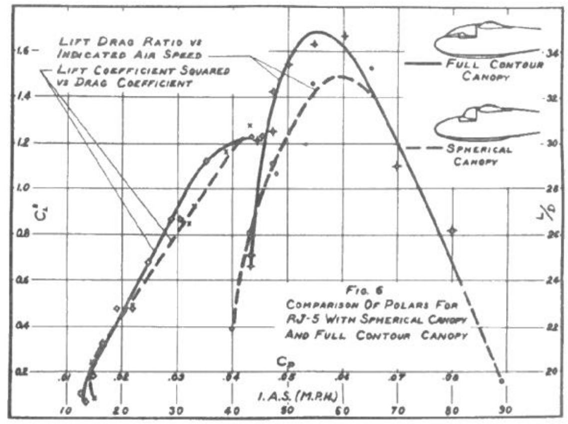


FIG. 6
COMPARISON OF POLARS FOR RJ-5 WITH SPHERICAL CANOPY AND FULL CONTOUR CANOPY

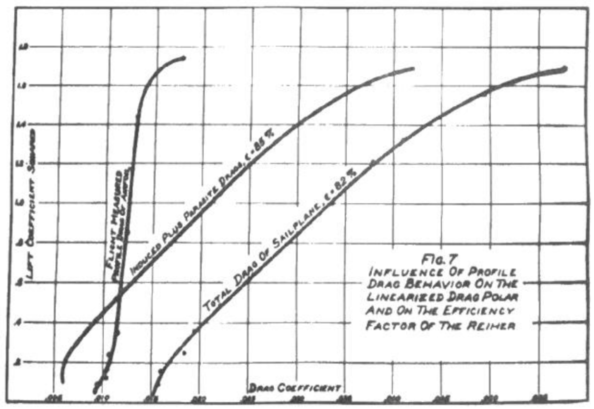
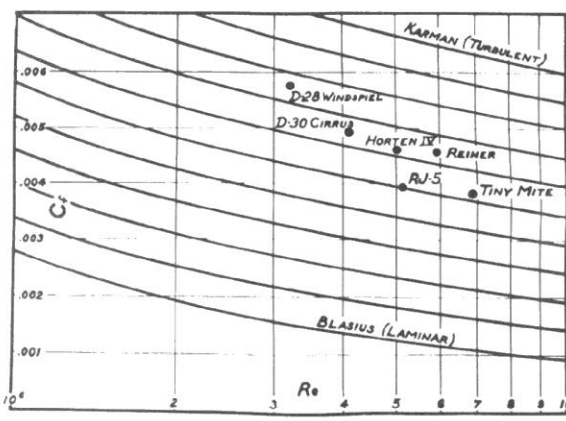


FIG. 7
INFLUENCE OF PROFILE DRAG BEHAVIOR ON THE LINEARIZED DRAG POLAR AND ON THE EFFICIENCY FACTOR OF THE REIHER

Fig. 8 Profile Drags of Various Sailplanes Based on Wetted Area.



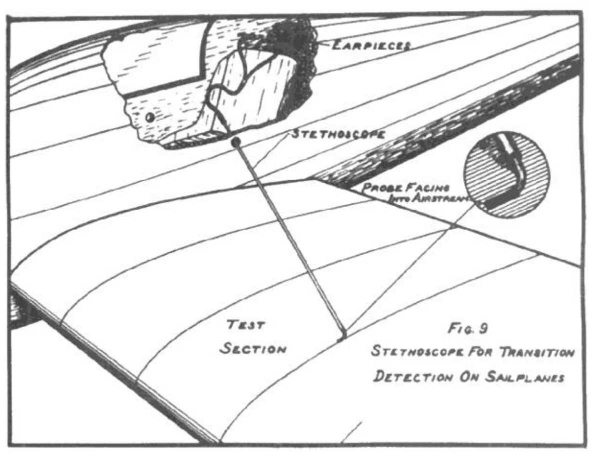


FIG. 9
STETHOSCOPE FOR TRANSITION DETECTION ON SAILPLANES

manner to write a prescription for improving the external geometry so that the sailplane will achieve a maximum performance. The emphasis which must be placed on either the bettering of effective aspect ratio or the reduction of drag depends on the application for which the sailplane is being developed. If it be for record-breaking cross-country flight, during which the sailplane will be flown in strong thermals of large size, then the emphasis should be on drag reduction. If it is to be for competition, during which the sailplane will fly under adverse and varied weather conditions such as those that occur at any contest, both a high effective aspect ratio and a low drag are important. In general, those changes which yield the largest improvement for the least amount of work should be made first.

THE BOUNDARY LAYER CONCEPT APPLIED TO SAILPLANE AERODYNAMICS, SEPARATION.

In sailplane aerodynamics the goal is a sailplane over which the flow will be completely laminar from a lift coefficient of nearly zero up to a lift coefficient at which minimum sinking speed occurs. This goal has not to date even been approached. The extent of the laminar flow over a complete sailplane in free flight has not yet been determined.

In spite of such a lack of knowledge of the laminar boundary layer, however, the concept of the boundary layer is important in analyzing the aerodynamics of a sailplane. One feature of the linearized drag polar is that it reveals the development of a separated turbulent boundary layer over the airfoil. As the separated boundary layer spreads forward on a wing with increasing angle of attack, the pressure drag of the wing increases. If separation occurs at comparatively low lift coefficients, the progressive forward movement of the separated boundary layer will be clearly shown by a low Oswald efficiency factor for the wing. Since the plain airfoil without a fuselage generally has an efficiency factor of nearly 100%, especially if designed for minimum induced drag, one must conclude that a low efficiency factor is due entirely to poor flow control in the wing root.

As soon as the flow in the wing root has been suspected of separating at lift coefficients below that of a plain wing, one has available a beautiful tool for studying the separation of the boundary layer. This tool is relatively simple to use and the interpretation of the results achieved is straightforward. Wool tufts fastened to the outside of a sailplane and photographed in flight show directly the region of the separated flow. In Fig. 3 is illustrated a systematic tuft study of the Reiher which was made at DFS. The photographs are correlated against a linearized drag polar, the data for which was obtained from Dr W. Spilger, also at the DFS. One sees immediately that the linear portion of the curve extends to $C_L^2 = 1.2$. At this point, separated flow is clearly seen on the fuselage near the trailing edge of the wing.

Since separation of the turbulent boundary layer always occurs when the adverse pressure gradient along the flow direction becomes excessive, one must find some way to reduce the pressure gradient if evidence of early separation is found on a sailplane. A comparatively simple solution consists of expanding fillets which can be installed in the wing root. Another simple solution is a process which was developed as a cure for the Laister-Kauffmann TG-4A, namely use of the "Flat Top" (Fig. 4). In this latter case, the entire superstructure above the wing was cut down to the main steel tube longerons. A blown bubble was employed in order to streamline the projection of the pilot's head, which of necessity protrudes above the fuselage lines. This modification raised the efficiency from 67% to 91%.

The best solution, however, is that offered by a shoulder-high intersection when it is used as it was by Dr A.M. Lippisch on the Fafnir II. On the RJ-5 (Fig. 5) R.H. Johnson used an ever higher position for the wing, since it permitted a relatively simple fillet to be fitted at the rear of the wing and the fuselage.

Because the tendency of the boundary layer to separate is intimately connected with the intrinsic energy in the flow over the wing root, it may happen that an improperly designed canopy can cause early separation. This is true if the flow is accelerated to high veloci-

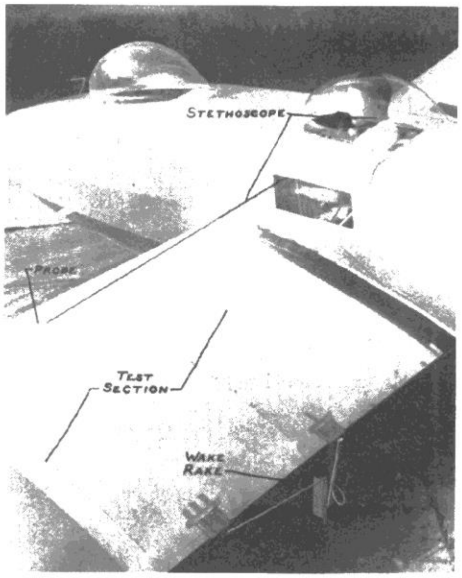


Fig. 10 Stethoscope Being Used on Upper Surface of Sailplane Wing. Integrating Rake for Profile Drag Measurement is also shown.

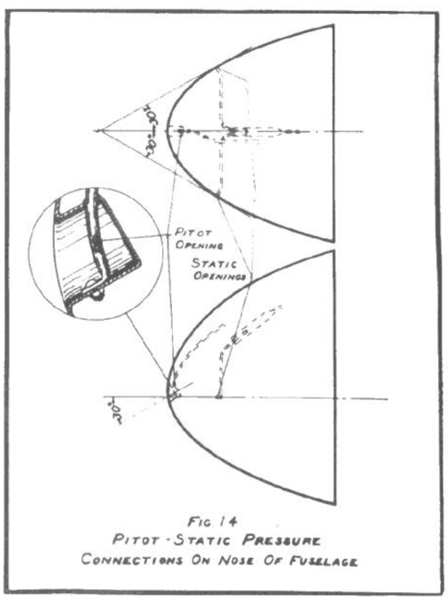


Fig. 14
Pitot - Static Pressure
Connections On Nose Of Fuselage

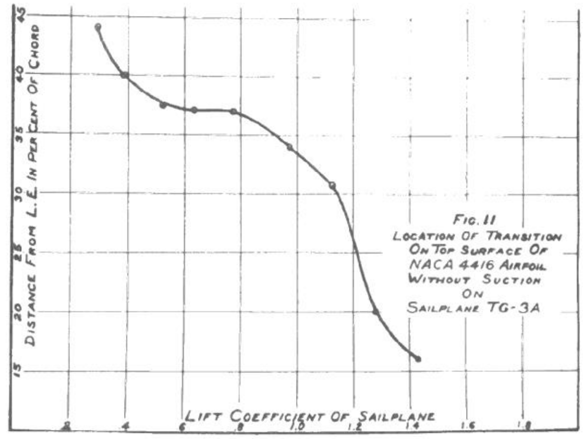


Fig. 11
Location Of Transition On Top Surface Of NACA 4416 Airfoil Without Suction On Sailplane TG-3A

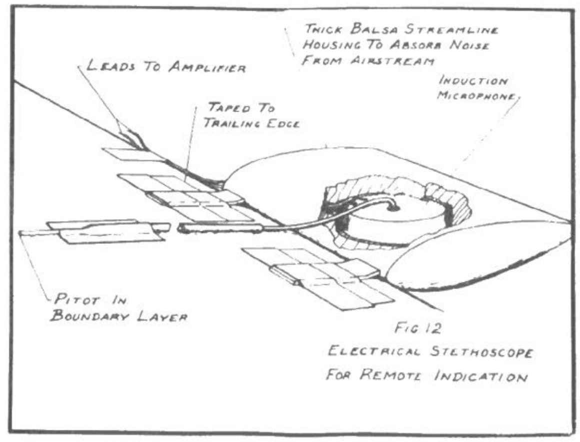
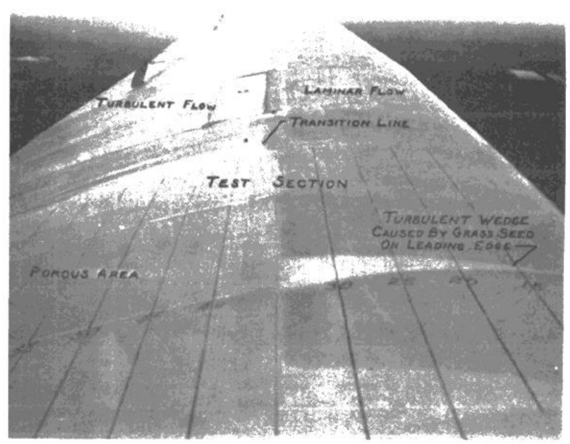


Fig 12
Electrical Stethoscope For Remote Indication

Fig. 13 Dew Evaporation Technique for Transition Detection.



ties over a relatively blunt canopy. A canopy with a sharp break will also certainly initiate early separation. A good example of excessive acceleration is shown in Fig. 6, in which a spherical canopy and a full contour canopy on the RJ-5 are compared on the linearized polar.

In connection with canopies, it should be mentioned that jets of air escaping into the high speed flow at a wide canopy gap are a sure cause of separation. Gaps should be sealed with adhesive tape to ensure a leak-tight joint.

In using the linearized drag polar for the analysis of very low drag sailplanes, those for which the profile drag is nearly equal to the parasite drag, one must consider the influence of the profile drag behavior on the efficiency factor. In the Oswald performance equation, the profile drag is assumed to remain constant with variable lift coefficient up to the point where the linearized polar begins to fall off. In general, for the classical airfoils the profile drag rises slightly with increasing lift coefficient. Such a behavior would appear on the linearized polar as an increase in induced drag. In Fig. 7 is shown an analysis of the Reiher based on the profile drag measured in flight on the DFS Meise. The profile drag was subtracted from the total drag obtained in flight, yielding the polar of parasite plus induced drag. In this curve it may happen that the parasite drag can also be a function of lift coefficient. However, it is quite evident that the efficiency factor of the Reiher could be raised and that the wing root flow separates at quite low lift coefficients.

INFLUENCE OF THE TRANSITION FROM THE LAMINAR TO THE TURBULENT BOUNDARY LAYER ON A SAILPLANE.

Having considered the influence of separation on the efficiency factor of a sailplane, it is next necessary to take up the influence of the geometry of a sailplane on the extent of the laminar boundary layer. As a general rule the extent of laminar flow over a sailplane determines the drag of the sailplane. On the present day sailplanes, operating between Reynolds numbers of one and three millions, the laminar skin friction is about one-fourth that of the turbulent. Efforts to reduce the profile drag and the parasite drag should then be directed toward increasing the laminar extent. Laminar airfoils are one possibility. However, the same consideration as that used in the design of the laminar profiles can be used to increase the extent of laminar flow over a fuselage: a falling pressure along the fuselage should be maintained as far back as possible.

It is quite clear that in order to increase the laminar extent one must know what extent of laminar flow is present on today's sailplanes. The proportion of laminar and turbulent flow can be determined by plotting the minimum drag coefficient based on total wetted area, as shown in fig. 8. In this figure the area between the turbulent and laminar friction curves is divided by a series of lines, each representing the proportion of area covered by laminar flow. Examination of this curve shows the progress made by RJ-5 over sailplanes of previous design. It also shows that there is considerable room for improvement.

The method of Fig. 7 fails, however, to point out which regions are laminar and which are turbulent. It is merely a gross estimate. For detecting the exact position of transition of the flow there is available a relatively simple tool, the stethoscope (Fig. 9). With this device the observer listens to the sound of the flow as he moves the probe over the surface. When the transition region is reached by moving the probe in the direction of the flow, a loud hissing noise is heard. This is the noise of the turbulent boundary layer. The stethoscope may be made in the form of a long steel tube with a probe at its extremity. A rubber tube connects this tube to the earpieces (Fig. 10). By means of this tube the observer can reach out into the boundary layer of a wing and detect the position of transition at different lift coefficients. Fig. 11 is an example of such an exploration.

When a region of the airfoil far out on the wing must be examined for laminar extent, however, an electrical stethoscope must be used (Fig. 12). By installing the telephone microphones inside the fuselage and leading the probe out through a hole, one can study the flow over a fuselage with the same arrangement.

In case the laminar extent over an entire wing or even an entire sailplane is desired, there is available the film evaporation technique which depends on the fact that the „austausch" is very much lower in the laminar flow than in the turbulent flow. In Fig. 13 is shown an example of this technique. For this photograph, dew was allowed to settle on the wing at dawn. During takeoff the dew evaporated very quickly in the region of turbulent flow but remained on the laminar region for as long as from one to six minutes, depending on the moisture in the atmosphere and the air temperature. In place of dew one can spray onto the surface water in a fine mist from a spray gun.

Another even better film is that obtained by spraying the surface with a 5% solution of napthalene in petroleum ether which has a boiling point of 60^{0} C.

The film techniques can be used to examine a complete sailplane at one lift coefficient. A landing must be made as soon as the transition is clearly shown and a photographic record of the laminar extent made. It is also possible to photograph the indication in flight. By making a series of such flights one can determine the behavior of the flow over the complete range of lift coefficients.

From photographs such as Fig. 13 one will be surprised to find the detrimental influence of protuberances on the nose of a fuselage or of small geometric discontinuities on the leading edge of a wing. After seeing the effect of even a grass seed, the careful sailplanist will no longer permit a pitot-static tube to be mounted on what could be a nice, clean laminar fuselage nose. Venturis for driving turn indicators, in addition to the fact that they possess only 5% efficiency, cause severe drag increments due to their initiating turbulent flow. Jets of air escaping outward through a gap are sure to initiate the transition. Corners parallel to the flow, whether projecting outward or inward, are also certain to generate a turbulent wake. (The spreading of the turbulent wake behind any source of flow transition takes place along a wedge having an included angle of 20^{0}.) Such corners perpendicular to the flow as those appearing on some canopies are certain to cause transition if not even separation.

Another serious cause of transition and high drag are ventilators in the canopy. These may be either the round rotable type or the side window of the sliding variety. These ventilators are usually placed in a region on the side of the canopy where the pressure is negative and an outward flow takes place. In this position they do the most damage to the performance of a sailplane. A much better arrangement is to place a slot at the intersection of the canopy and fuselage. This is a stagnation point and air will flow into the fuselage under pressure to cool the pilot. The inward flow of air will in turn tend to stabilize the boundary layer so that it will remain laminar much farther back on the canopy.

From these various causes of transition one can see clearly that the nose of the fuselage should be free of all protuberances. The release should be built internally using a guillotine to cut the line, the pitot-static should be built into the nose (Fig. 14) and the skid should be faired into the fuselage as was done on Reiher. The skid, however, should be rounded on the bottom so as not to present sharp corners parallel to the flow. Any gaps, unless they are in a region of positive pressure, should be sealed with adhesive tape.

Toward the rear of the fuselage, where the flow would normally be turbulent, it is not so important to maintain a smooth geometric surface, but even so surface roughness is always a consideration in reducing turbulent shearing stresses. For this reason the surface should be smooth.

PROFILE DRAG REDUCTION.

For many years the sailplane designer has had to rely on windtunnel measurements for data on the drag of various airfoils. In some cases the windtunnel results were obtained in a turbulent flow. In other cases the data had to be extrapolated to the correct Reynolds numbers. However, it was only in a few rare instances that profile drags were measured directly on the sailplane in flight 1). Without flight measurements it was not possible to determine the geometric accuracy required of an airfoil in order to obtain a minimum in

1) See reference 10 on page 32 and 33

profile drag. It is now possible to make profile drag measurements in flight by the relatively simple method using an integrating momentum loss rake 1). A drawing of a rake suitable for sailplanes is shown in Fig. 15. This rake may be fastened to the trailing edge of a wing with adhesive tape and may be moved to different positions along the span (see Fig. 10). Figs. 16 and 17 show some typical measurements made on RJ-5.

This simple instrument enables one to determine the influence of surface geometry on the profile drag of the well-known airfoil for sailplanes, G-549. In Fig 18 the influence of surface waviness on the profile drag is clearly evident. In fact, one can conclude that the accuracy of holding the geometry of an airfoil is more important than is the selection of the airfoil. After all, the feature which distinguishes one airfoil from another is its profile drag behavior over the useful lift coefficient range. If the boundary layer is allowed prematurely to become turbulent by surface discontinuities, then that airfoil no longer behaves as was predicted from measurements on a smooth airfoil. It can also happen that when a wing is carefully contoured the profile drag is less than that measured in a noisy, turbulent windtunnel since noise and turbulence are each pressure fluctuations capable of initiating transition.

It therefore behooves the careful sailplane constructor to make the leading edge wavefree at least to a point on the airfoil where transition would normally occur as a result of laminar separation. On the DFS Meise the discontinuity due to the cloth's sagging at the rear of the plywood leading edge causes the transition on the top surface to be fixed at this point over the complete range of speed of the sailplane (see Fig. 18). One way to prevent this cloth sag is to use a much closer rib spacing or to run the plywood farther back on the wing. In Fig. 19 we can see what the profile drag of the G-549 airfoil would be if this cloth sag did not exist. This was computed from the formula of Squire and Young 2), assuming that the transition on top and bottom surface would behave in the rationally extrapolated manner shown in Fig. 18.

Since it is nearly impossible to construct accurately a wing with a wavefree surface, it has been found most practical to fill in the low areas with a pyroxilin putty and then contour the surface by sanding. For filling deep hollow areas, it is sometimes necessary to use layers of cloth in addition to the putty. During the sanding, the waviness gage (Fig. 19) is used as a guide. This process may appear tedious, but since the profile drag reductions accomplished are of as high as 50%; there is no doubt about its effect on high speed performance. For example, on the DFS Meise, with smooth leading edge and no sag in the fabric, the profile drag would go from 0.0128 to 0.0065 and the overall drag from 0.019 to 0.013. The maximum glide ratio would rise from 25 to 1 to 29 to 1 and the sinking speed in high speed flight would be 32% less. Such gains are worth a few hundred hours of careful work.

Over an airfoil, gaps and joints are even more effective in causing transition than on a fuselage because the pressure gradients are more severe for the two-dimensional case. For this reason, dive brakes should be fitted to the fuselage rather than to the wing. If put on the wing, the flight path control should be in the form of a dive flap on the bottom of the wing where the pressure gradients are less severe.

For the same reason gaps on ailerons and openings for hinge brackets should be sealed closed. Hinge brackets on ailerons, flaps or elevator should be internal so as not to cause a seperated flow over the control surface. The same holds true for control horns.

Much debate has taken place on the pros and cons of laminar airfoils for sailplanes. So far only a moderate laminar airfoil NACA 63_2-615 has been tested on the sailplane RJ-5. While the results have been gratifying, the measured profile drags have not been so much smaller than the extrapolated values of G-549 in Fig. 19. However, laminar airfoils which have the negative peak pressure much farther back, say at 60% of the chord, are still untried on sailplanes. Perhaps a carefully contoured wing using the profile NACA 66_2-415 3) would permit a profile drag coefficient reduction of 0.002 on RJ-5. This would mean an increase in glide ratio to 44:1. The sinking speed at high speed would decrease 20%.

1) See reference 11 on page 33.

2) See reference 12 on page 33.

3) See reference 12 on page 33.

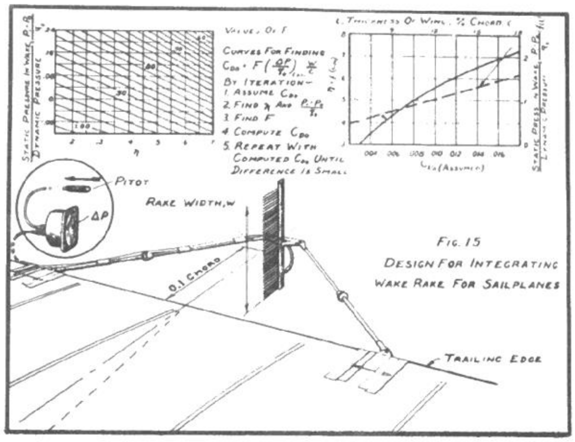


Fig. 15 Design For Integrating Wake Rake For Sailplanes

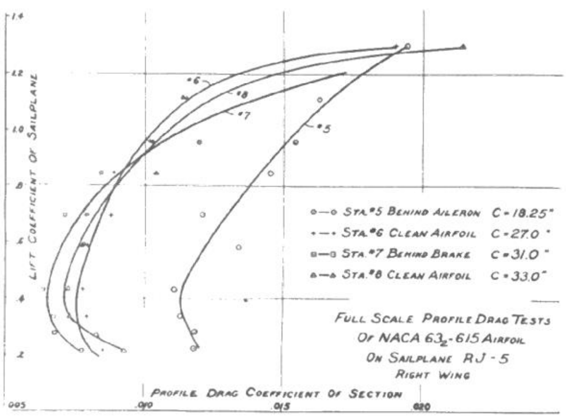


Fig. 16 Flight Measured Profile Drag of Section NACA 63_2-615 on RJ-5 Right Wing.

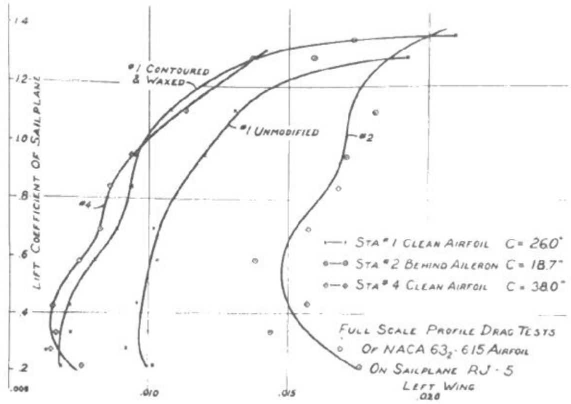


Fig. 17 Flight Measured Profile Drag of Section NACA 63_2-615 on RJ-5 Left Wing.

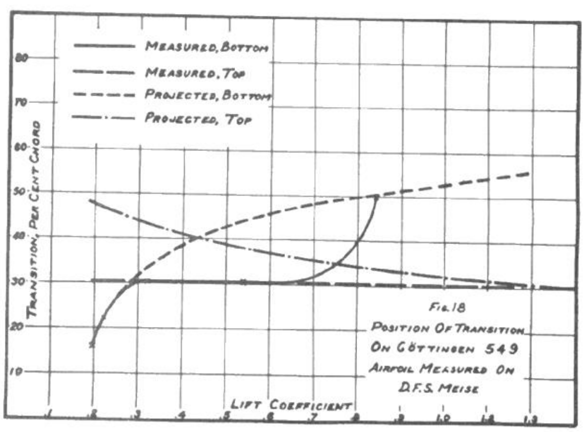


Fig. 18 Position Of Transition On Göttingen 549 Airfoil Measured On D.F.S. Meise

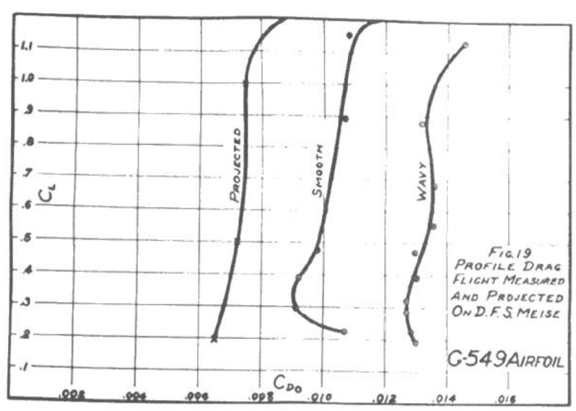


Fig. 19 Profile Drag Flight Measured And Projected On D.F.S. Meise

TIP DESIGN AND DRAG.

1. Twist: Every sailplane designer is aware of the necessity for designing the tip so that tip stall does not occur. A very useful device for preventing tip stall has been that of "wash out" or negative wing twist. On highly tapered wings having taper ratios of 3 to 1 or higher, twist has been used to reduce the induced drag. The true reason for using twist, however, is that it retains lateral stability near the stall. The one serious disadvantage of twist is that the profile drag at high speeds cannot be minimized. This is especially true of laminar profiles which have a laminar bucket over a rather limited lift coefficient range 1). In this respect it is interesting to examine the results obtained with RJ-5, which has a twist of only 1.6° with a taper ratio of 3.5. Since in Fig. 21 the efficiency factor is seen to be 98%, little could be gained in an attempt to reduce the induced drag by more twist. In addition, the lateral stability in the stall is soft and there is, therefore, no reason to consider more twist for the sake of preventing tip stall. In looking for an explanation of this apparent anomaly one is forced to conclude that tip stalling was prevented by the smooth leading edge which permits the tip to develop a high lift coefficient. This behavior is quite evident from the tests of smooth airfoils and those of standard roughness in windtunnel results 2) in which the smooth wing at RN = 1 million developed a lift coefficient of 1.26, whereas the rough wing only 1.18.

For controlling tip stall on the sailplanes Tiny Mite and Screamin Wiener, wing tip slots were used. Such slots are generally exceedingly detrimental to performance in that they reduce the effective aspect ratio by as much as 8%. The reduction is caused by an actual loss of lift curve slope at the tip or by a rapid drag increase occurring with increasing angle of attack. In any case, leading edge slots have no contribution to make to high performance sailplanes.

2. Wing Tips: Low loss tip design is a promising field of activity for sailplane research. Hoerner 3) has shown that the induced parasite drag of a wing due to the high shearing stress in the tip vortex can be quite high. Distributions of profile drag along the span show a high peak in profile drag at the tip. If this could be reduced, a considerable gain in performance would result at the higher lift coefficients, i.e. in circling flight.

A rationally designed tip should have a low induced parasite drag and low effective parasite drag and should develop a high lift coefficient. In Fig. 22 are shown results of windtunnel tests of a number of wing tips plotted as linearized polars. Tip # 5 displays the best compromise of the three desired properties. This is the tip proposed by Hoerner 4). A tip of essentially this design was used on RJ-5.

In connection with tip design the streamlined body of revolution (tip tank) should be mentioned. In Fig. 23 a tip tank is shown installed on a Meise. A tip tank on each wing yielded in flight test an increase in maximum glide ratio of 1.6, from 23.5 to 25.1, but at the same time showed an increase in drag at low lift coefficients of about 0.001. The flow around such tanks suffers because the intersection of tip and wing is a source of early transition. Consequently the high speed drag is increased.

ANGLE OF INCIDENCE OF WING.

Shortly after the era of ridge soaring, efforts were made to maximize the glide ratio by choosing a fuselage shape and an angle of incidence of wing that at maximum glide ratio would permit the fuselage axis to be exactly in the direction of the induced flow of the wing at the lift coefficient needed for maximum glide ratio. This concept has been followed in general by most sailplane designers, principally because it permits a good angle of attack for the wing when the sailplane rests on the ground. With the advent of airplane tow

1) See reference 12 on page 33.
2) See reference 12 on page 33.
3) See reference 13 on page 33.
4) See reference 14 on page 33.

and less emphasis on take off at maximum lift coefficient, such high angles of incidence are no longer necessary. Because record-breaking cross-country soaring required high speeds between thermals, the modern sailplane is designed for low minimum drag. This means that at high speeds the fuselage should be aligned with the direction of flight and not pointed in a nose-down attitude as is common with sailplanes having a high angle incidence. On RJ-5 the wing was set at 2.5° from the zero lift line. In other words, the fuselage is aligned with the flight path at $C_L = 0.25$. In order to assist in take off, split flaps hinged at 50% C were used as a take off and landing aid and also as a dive flap.

BOUNDARY LAYER CONTROL BY SUCTION.

In Fig. 9 the reader will see a sailplane set up as a research tool for boundary layer control studies. With this sailplane a very promising method of stabilizing the laminar boundary layer was investigated 1). The technique utilizes suction through the fabric on a wing made porous by pricking with a needle. An average inward suction velocity of only 0.0005 of the flight velocity reduced the drag of the NACA 4416 airfoil from 0.008 to 0.004. There are still many problems to be solved before this elegant method can be applied to sailplanes in general. However, these problems are not insurmountable, and since the reward is so high an early solution and application will be found.

CONCLUSION.

In this paper the author has attempted to convey to sailplane designers some of the principal boundary layer concepts which have been found to lead to higher performance sailplanes. Many of the techniques are directly applicable to existing sailplanes. In fact, it can be generalized that the performance of any existing sailplane will be improved by at least 10% if the constructors will follow a few of the simple suggestions discussed in this paper. Above all, the author hopes that he has demonstrated the usefulness of a method combining flight measurement, analysis first by the linearized polar and subsequently by profile drag measurement, tuft investigation, and transition detection. With these powerful tools, a direct approach to the control of viscous aerodynamics on sailplanes becomes a reality.

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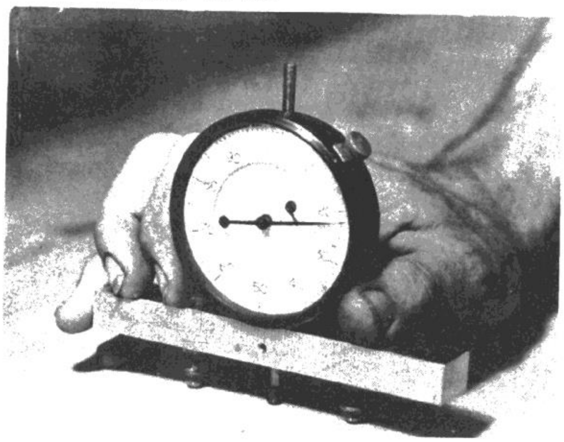

Fig. 20 Instrument for Measuring Waviness of Airfoils.

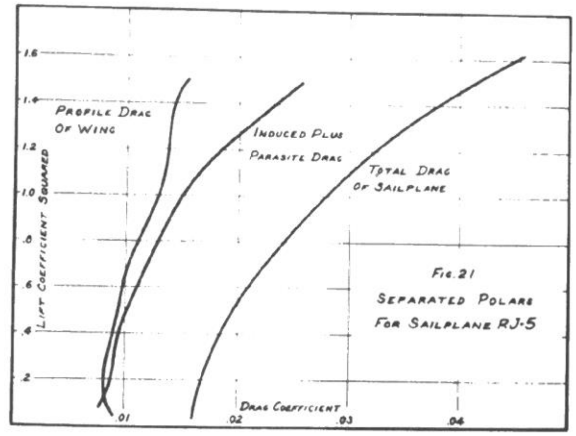

Fig. 22 Polars of Various Wing Tip Designs.

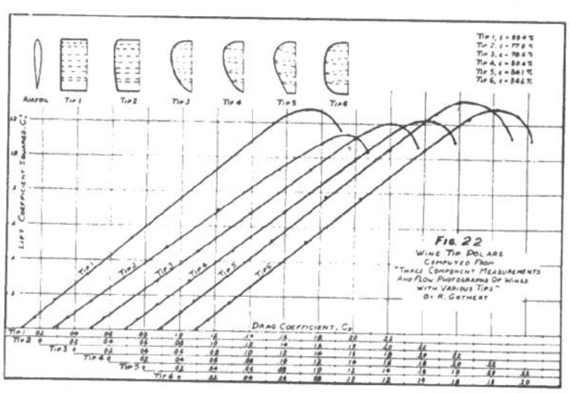

Fig. 23 Body of Revolution on Wing Tip of DFS Meise.