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16. Abstract

The article discusses the causes of drag in gliders. The importance of maintaining laminar flow is emphasized. The problems of surface (or lack of) smoothness are outlined.

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DRAG REDUCTION FOR GLIDERS

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3. WING PROFILE SELECTION

When selecting the profile of a glider, two aerodynamic criteria are used, and these are even more important than selecting the wing plan form: The profile should result in the maximum possible travel velocity and the most favorable conditions for slow flight. It is difficult to obtain an overview about the influence of the profile on the travel velocity, with consideration of circular flight. Special investigations are required for this [1]. Even for wings with very different profiles, one can obtain the same travel velocity; for example, if we select a profile whose drag is especially low in the high-speed range, in general this advantage is compensated for by the large drag values for slow flight conditions, and vice-versa. If we consider previously-measured profile polars, it is found that neither one of the extremes will provide the optimum travel velocity. Instead, it seems more favorable to use profiles with extremely wide laminar depressions, which favors both fast and slow flight conditions. [2] gives an extensive discussion of this, but does not consider the special meteorological conditions.

In addition to the arguments presented above, which are based on a consideration of a travel velocity, profiles with a wide laminar depression are favorable for other reasons: when there are weak upwind conditions, it is easiest to stay up with them. When the upwind increases with altitude, the critical altitude is lower than with a different kind of profile. If the aircraft goes below this critical altitude, then a landing must be performed. Of course, one can use a profile which is especially favorable for fast flight, and it is also advantageous for weather conditions with very strong but very distant upwind fields.

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*Boblingen. Reworked version of a lecture at the OSTIV Course in 1964 in Varese, Italy.

**Numbers in margin indicate pagination in foreign text.

However, it seems that such situations are rare.

It is not optimum from an aerodynamic point of view to make a wing with a single profile over the entire wing. This is because, in addition to the high travel velocity, the profile on the outer wing should satisfy additional requirements.

For example, the angle of attack range between zero lift and maximum lift along the outer wing should be larger than for the inner wing, in order to provide good flight characteristics for slow flight. Beyond the maximum lift point, the decrease should be slow, and gentle. Finally, the profile of the outer wing should not have any pronounced laminar depression. Otherwise, for fast flight, because of the elastic twisting of the wing, the outer wing would fall out of the laminar depression at low c_a values and this would then become an effective brake. When tight circles are flown, the outer wing, which is located lower is subjected to a similar danger, but at this time it occurs at high lift values. It is especially important that the tail rudder effectiveness is not compromised by an inappropriately-selected profile.

It is not easy to satisfy these additional and contradicting requirements without a certain reduction in the travel velocity. This is because the Reynolds numbers along the outer wing, $0.5 - 1.0 \times 10^6$, are already quite small. The author of [2] gave a summary of several profile shapes, whose measured polars do satisfy the previously-mentioned requirements, and the requirement for a high travel velocity.

4. DRAG REDUCTION BY KEEPING THE FLOW LAMINAR

The previous discussions about the selection of suitable wing plan forms and profile shapes do not allow a great deal of flexibility to the designer. Considering the profile selection, he is mostly dependent on wind-tunnel measurements. /724 When he selects the wing plan form, he does have certain advantages compared with present-day designs, but overall he cannot achieve a great deal of progress. In contrast to this, if the boundary layer is maintained laminar, which amounts to a reduction in the friction drag, then many more possibilities open up. For example, a wing in a completely turbulent flow can have more than twice the profile drag than a wing whose boundary layer remains laminar, at least partially.

This means that the principle of keeping the flow laminar

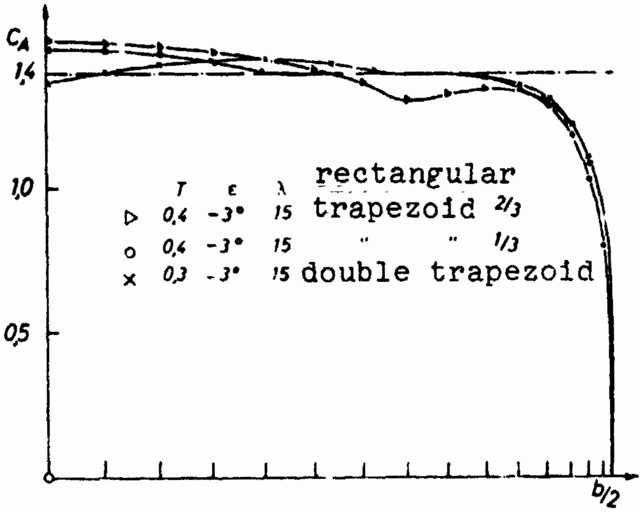

Figure 11: Lift distribution for rectangular wings and double trapezoid wings with $\lambda = 15$ and $\bar{c}_a = 1.4$.

represents the most effective leverage for reducing the drag, which should be used to advantage in any aircraft design. Of course, the possibilities can only be taken advantage of completely, if this principle is followed for a new design, starting at the beginning. Because of the great importance of this principle, we will briefly discuss the laminar-turbulent transition phenomenon, and then we will discuss the conditions for keeping the flow laminar.

The thin "laminar" boundary layer which flows in a smooth manner and which first forms on the surfaces of a body in a flow, normally continues to increase its thickness downstream in a continuous manner. In the beginning the state is stable, and is not sensitive to disturbances, but the state rapidly becomes unstable. Whether or not this unstable boundary layer becomes turbulent earlier or later on, depends on the one hand on the degree of the instability and also on the magnitude of the perturbations, which comes from the external flow or from the wall, and are introduced into the boundary layer. Except for drastic changes, such perturbations which directly cause turbulence are amplified in an unstable boundary layer. This is a process which requires time and a certain path length. It is clear that major initial disturbances will produce turbulence earlier for otherwise the same conditions. However, if the perturbations remain sufficiently small, then the measure of instability or the type of the perturbation amplification plays a major role. In aircraft, these perturbations are practically only due to the unevenness of the surfaces, that is, the roughness features and the waves in the surface. In the case of rigid and impermeable surfaces, the amplification process is determined decisively by the pressure variation in the flow direction.

The laminar boundary layer, for example, can be stabilized by a pressure drop, so that the transition only occurs at Reynolds numbers of $Re > 15 \times 10^6$. The Reynolds number is formed with the path length, which extends from the leading edge of the body to the transition point*. When there is a pressure increase, on the other hand, the corresponding Reynolds number can be reduced to $Re = 2 \times 10^4$, that is, about 1/700 of the value. When there are zero pressure gradients, for example, in the case of a flat plate, then the corresponding Reynolds number of transition is about 3×10^6.

km/h	m/s	Re/m
72	20	1.33×10^6
108	30	2×10^6
144	40	2.66×10^6

It is easy to find out what these numbers mean for gliders, and the table gives several Reynolds numbers for a path length of one meter. For a wing with a chord of 1 meter, for example, a constant pressure is sufficient to maintain the boundary layer over the entire chord, even for fast-flight conditions (at 40 m/s.) It is only at a length of about 1.1 meters that the Reynolds number would reach a value of 3×10^6 and the boundary layer would become turbulent. On the other hand, when there is a pressure increase, and the incident velocity is 20 m/s, a path length of 1 cm is already enough to completely develop turbulence, for example, if one wishes to maintain the flow laminar over a body surface flying at a fast speed at a length of more than 2 meters, then one needs at least a small pressure drop for stabilizing the laminar boundary layer. Expressed differently, in the case of a glider wing, transition always occurs downstream of the point of minimum pressure. For a smooth fuselage, the transition will occur already somewhat ahead of a pressure minimum, because of the larger Reynolds numbers.

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*At a velocity of $u = 40$ ms (145 km/h), $= 15 \times 10^6$ means a path length of 5.6 meters!

The pressure variation is determined by the shape and incidence angle of a body in a flow. It is clear that the exact knowledge of the relationship of the body shape as related to the pressure distribution using experimental and theoretical methods, is important for maintaining the flow laminar.

On the other hand, from the transition Reynolds numbers, one can see that it is relatively simple and easy to maintain the flow laminar in the velocity range of gliding, when there is a suitable pressure variation, with the condition that the additional influences, that is, the perturbations, of the laminar boundary layer, can be maintained sufficiently small.

Fortunately, the free atmosphere in general is such that it introduces practically no perturbations to the boundary layer. Many glider pilots believe that the gustiness of the thermals has an unfavorable effect on laminar profiles. However, gusts primarily change the incident flow direction for the aircraft, and this change is probably the primary negative factor of gustiness. A perturbation due to the incident flow, therefore, only occurs in tail surfaces, if they reach the turbulent wake of the wing.

This means that inaccuracies in the surface, such as roughnesses /725 and waves, are possible perturbations for the most part. Fortunately, the boundary layer only reacts to such things when the perturbation magnitude has reached a certain amount. The limiting height beyond which transition is influenced is called the critical roughness height k, and is about 1/13 of the boundary layer thickness. Figure 12 shows critical roughness height for a flat plate having a chord of 1 meter, and for two typical Reynolds numbers. If one wishes to have these values for other chord values T and Reynolds numbers $Rc = \frac{U_\infty t}{\nu}$ *, one should use the formula $\frac{k}{t} = \frac{0.35}{\sqrt{Rc}} \cdot \sqrt{\frac{x}{t}}$. If the velocity remains the same, the height k for example varies along the span according to $\sqrt{t}$. If the body is pointed with a factor T = 0.5, then k must be about 30% smaller along the outer wing than in the inner wing. The values given for the flat plate are important references for values which are permissible for the profile, if we consider the fact that the profile boundary layer is in general

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*U_∞ = flight velocity

ν = kinematic viscosity

20% to 30% thinner than for the flat plate, because of the pressure drop. This means that the critical roughness heights from the profile nose to the maximum profile thickness point are somewhat smaller than shown in Figure 12. These are lower limiting values, which are certainly not "felt" by the laminar boundary layer in the plane case. In the case of body surfaces, that is, three-dimensional flows, the critical roughness heights are also somewhat lower than shown in Figure 12. The values for the body front part must then be multiplied by a factor of between 0.7 and 0.6.

The reason why the boundary layer along the body front part is thinner for a flat plate under otherwise the same conditions is primarily due to the increase in the body circumference. The boundary layer skin which surrounds a body in this way is given a thinning-out in a certain sense. Therefore, it grows slower in the flow direction than for a flat surface. Conversely, the conditions are opposite for a contraction of the body cross-section: the boundary layer material flows together and can become more than twice as thick as the case mentioned above.

Therefore, we should realize that it is not at all true that a small oil spot on the surface will lead to turbulence, as one often hears. Instead, not even a coarse sandpaper will lead to impermissible roughnesses. The requirements are also more stringent in the vicinity of the leading edge of the wing and the nose of the body.

How does one control the roughness height? In special cases, this is done by measurement, of course. In practice, the touch sense of the fingers and the inner side of the hand are completely sufficient; (for example, one can test Tesafilm, which is about 8 x 10^{-2} mm thick) A roughness which cannot be felt is, as a rule, considerably below the critical value. Finally, we should emphasize that an ideally-smooth surface cannot perform more towards keeping the flow laminar than a rough surface, which does not exceed the critical amount at any point.

Figure 12 shows two dashed lines, which have nothing to do with keeping the flow laminar. They are the permissible roughness magnitude for boundary layers which have already become turbulent. Up to this magnitude, the surface is "aerodynamically smooth". Larger roughnesses increase the friction drag for a turbulent boundary layer, for example, if the roughness height is doubled, it is increased by about 20%. The

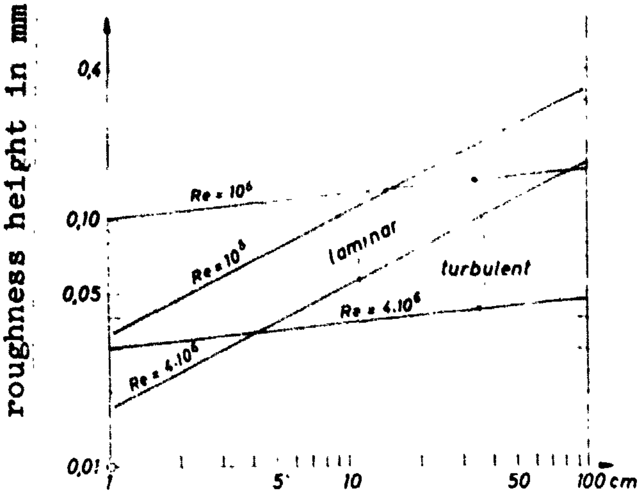

Figure 12: Critical Roughness heights for laminar and turbulent boundary layers for a flat plate 1 m long and for two Reynolds numbers.

values given are safe limits, similar to the laminar boundary layer. For example, in the region of a pressure increase, somewhat larger roughnesses are still permissible. Figure 12 also, at the same time, shows the great influence of the Reynolds numbers. For a turbulent boundary layer, the surface must be smoother than for a laminar boundary layer, except for the first 100 mm.

The question of which surface waviness can be looked upon as being permissible is not to be easily answered. Probably there is no "permissible" waviness at all. According to theoretical investigations, a sufficient number of waves following one another will always produce a separation of the laminar boundary layer, even if the wave amplitude is very small. Therefore, it is not astonishing that at the same time transition takes place considerably earlier than for a surface without waves.

The periodic sequence of the identical waves is probably an exception in a real surface. On the other hand, single isolated waves will occur often. It is likely that a wave whose amplitude is not greater than the critical roughness height in Figure 12 will have barely any influence on the position of transition. However, it is possible that certain wavelengths are more dangerous than others because of a kind of resonance. This could be true for wavelengths of between 80 and 150 roughness heights. A premature transition in the first place means an increased friction drag, but also unfavorable conditions. For example, if the tail rudder on the outer wing is deflected, there is usually also a separation of the turbulent boundary layer, which can very rapidly lead to large resistance values.

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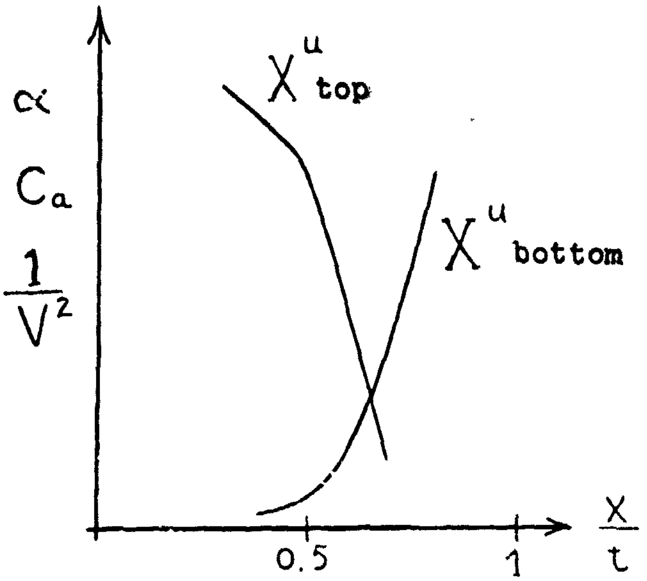


Therefore, one should not only control the quality of the surfaces but also the position of the transition fronts in flight tests. In the case of a wing, for example, the transition position for different angles of attack (or c_a - values, or velocities v) one should obtain a variation as given in the sketch. If wind tunnel meaurements are available for the profiles used, then by comparison one can establish whether the wind tunnel values were also achieved in flight, and where deviations occurred. When the transition position agrees, at the same time one also has a verification that the drag coefficients are the same as in the wind tunnel.

In a flight test, the observation of transition is not as easy as in the wind tunnel, where the soft singing of the laminar boundary layer can be heard through a tube, and can easily be distinguished from the rough noise of turbulence. Even when probes are installed, at least 20 points on each half span should be observable. Microphones for listening to the boundary layer are not suitable, because of their sensitivity to body noise. The same is for total pressure probes, because of the small stagnation pressures. My colleague, D. Althaus, therefore developed a simpler and safer method for observing transition on gliders, on which he will shortly report.

5. CURVED FLAPS AND BRAKES

After the short discussion about the requirements and control of keeping the flow laminar, we will now make some observations regarding brakes and curved flaps. Normally, a laminar boundary layer becomes turbulent in the brake flap area at the latest, either the flap is not a smooth continuation of the surface, or it is not hermetic with respect to the pressure difference between the upper and lower side of the wing. Both causes can be avoidable, and it is not always favcrable to go back to 70% of the profile chord, or even further, with the brakes. If curved flaps follow the brakes, the region between 50 to 65% of the chord will be the most favorable, because here the laminar boundary layer is already relatively thick, and therefore the critical roughness height is large. Also the profile thickness still affords substantial room for installation (of probes). In order to facilitate the hermeticity problem, the topside and lower side flaps should be installed in separate chambers, and the common axis should be made hermetic along the separation wall of the chambers. Because of the eleastic bending of the wing, the flaps can only be made continuous (with surface) using a covering strip which is elastically connected with the flap. The vertical gap between the covering strip and the wing skin should be 0.5 to 0.8 mm at a maximum. The covering strip should also seal off the flap chamber to a certain degree, if possible, because in the flow direction there will be a pressure increase in general, through which the flow can flow in along the rear strip gap and can flow out along the front one.

The curved flaps and the tail rudders are specially difficult, because of the small Reynolds numbers. Separate investigations will be required to obtain the really good solutions. It is desirable to have rotation axes on the topside of the wing from the design point of view. Aerodynamically, however, the flaps which are deployed downwards are especially vulnerable to separation, and the bend in the upper contour will increase this danger considerably.

A separation on the wing side not only decreases the rolling moment, but is intended to increase the tail rudder deflection. The increased drag amplifies the undesirable negative roll yaw moment.

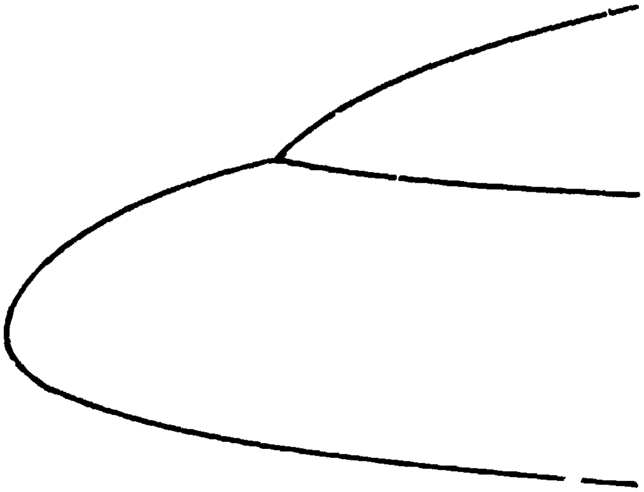
Such detrimental factors can be accepted for a tail rudder because the rudder is only deflected over short time periods, and usually with only small amplitudes up to about five degrees. On the other hand, the flap wing is deflected by +10 or -15°, and represents a long period installation. It is very important to know what the flap can do at these large angles. The low degree of success of older flap aircraft shows that this idea does not automatically lead to a higher performance, but instead requires specially-designed profiles [2]. Undoubtedly, the questions regarding flap profiles of gliders have only been touched, and advances are to be expected.

6. BODY

It is remarkable how seldom glider designers, who give so much attention to laminar profiles, exploit the possibilities of reducing the drag over bodies. Figures 1 or 2, or a simple calculation, show that the body drag is very important for fast flight. There are two possibilities: the boundary layer can be kept laminar along the body front part, and the surface area of the tail surface carrier can be reduced. The first possibility can reduce the drag to one-half of t completely turbulent bodies.

For fast flight conditions, the Reynolds numbers are about /727
6×10^{-6} up to the region of the wing leading edge. At these numbers, the boundary layer can easily be kept laminar by means of a slight pressure drop. However, one must have a suitable body shape and one must have a hermetic and smooth surface of the front part of the body. This means there can be no total pressure probes, cabin air conditioning, towing coupling, skids, water release holes, removable nacelles, or other over-critical roughnesses along the front part of the body. These requirements already represent serious difficulties, and have been realized in several gliders. However, there is still the problem of the pilot getting in and out of the aircraft. In spite of all the enthusiasm for perfect aerodynamics, the pilot must be given a primary importance, and must have sufficient comfort and safety. In many new designs, it has been overlooked that it is necessary to make the removeable part of the canopy hermetic and continuous with the body contour. Instead, one gains the impression that the solution decided upon was a minimum body cross-section with a pilot lying down , and

extremely long canopies. A close inspection shows all of the conditions for completely turbulent surfaces to be satisfied. Then one can see that an error has been made to confuse external elegance with aerodynamic quality. Such bodies are not any better in terms of drag than conventional body shapes, such as the Ka-6 aircraft.



There are various types where the canopy is designed according to the sketch shown. Because of the slightly concave corner, the laminar boundary layer separates in the central part and this leads to turbulent vortex strips on both sides of the canopy. Usually, this turbulent region then reaches the already-endangered wing root. Then, especially during slow flight, a secondary loss is produced in the region of the body wing transition point, which is then much larger than the friction loss at the canopy. Here again, the same holds true: one cannot expect a noticeable gain, compared with conventional canopy shapes.

However, if a certain degree of improvement is important, then one should be consistent and should evaluate every detail with the eyes of a boundary layer engineer. The body contour should not have discontinuities in the cross-section, for keeping the flow laminar, and the longitudinal section should not have any discontinuities either. This means a "strake retracted canopy shape" is a condition here. The "canopy" that is, the transparent part of the body, should consist of a front part connected with the body and a removable part.

The body contour should be derived from the shapes of thick laminar profiles, so that local overvelocities are avoided, and a monotonic will be maintained for moderate angles of attack or side slip angle.

If the front part of the body is completely smooth and hermetic, then one can attempt to keep the body layer laminar, also over the removable part of the canopy. This is best done by displacing the separation gap as far back as possible into the region with a larger critical roughness height. The smooth outer contour could probably be maintained even for daily aircraft use using a groove and spring design at the front and rear separation gap. Perhaps the separation gap could also be made hermetic at the same time. There is an underpressure of about 10 to 20% of the stagnation pressure at the outer skin in the region of the largest body cross-section. It will flow through porous parts out of the cabin. This causes a laminar boundary layer to become turbulent immediately. In earlier world competition, sometimes canopies were sealed with sealing strips. This method probably will make it harder for the pilot to get out of the aircraft, and cannot be looked upon as a solution of the sealing problem, (even if the roughness height of the strips is under critical).

It will probably be difficult to keep the boundary layer laminar over the rear separation gap of the removable canopy part. On the one hand, because of the pressure distribution and also because of the length change of the plexiglass due to temperature changes, a certain amount of play will be necessary. Nevertheless, the rear separation gap should not be developed as a ventilation gap, considering the body wing connection. Instead, there should be an elastic air-tight seal.

If one were to follow the typical concept of a smooth and hermetic front part of the body, and a laminar boundary layer up to the wing, then of course ventilation must be subordinated to this requirement. The supplied air could be taken off from an inlet diffusor or an air inlet cup, downstream of the transition point along the body side wall; for example, under the wing. Flat channels would then be used to direct the air into the cabin, and it would flow through slits into the canopy inner sides. The air to be removed should be allowed to pass through the body, and should emerge through a special opening near the spike, that is, along the body underside.

In the same way, the total pressure cannot be taken from the front part of the body. The total pressure probe consists of a tube open in the forward direction, and the wall thickness should be small compared with the inner diameter. There are many possibilities for installing the probe. The total pressure can be measured correctly everywhere, as long as one is outside of the boundary layer and out side of separation regions. However, there are restricted numbers of /728 points for practical reasons: It represents an obstacle for mounting the wings if mounted along the body sidewalls, if mounted along the body underside, there is a danger of contamination and damage. If the dimensions are small, then it is easy to penetrate into the boundary layer material if it is mounted on the back of the body. The tip of the rudder is an appropriate and often-used installation position, if the adjustment time of the air speed indicator remains sufficiently small. Usually this can be done using a pressure line with an internal diameter of only 3 mm.

The static pressure taps can also be installed in the total pressure probe (Prandtl tube). However, taps on a body cross-section are probably simpler and more effective, and they are installed about one control surface width ahead of the control surface. Four or more taps should make a cross along the circumference, and the position should be displaced 45° with respect to the vertical. When these taps are connected, then the average static pressure is quite independent of the oblique flow condition.

If transition on the body surface has been delayed to the wing, then one can consider even more the second possibility of reducing drag: the body cross-section is constricted, and in this way the surface exposed to turbulent flow is reduced. This at the same time corresponds to a useful boundary layer principle, in which most of the pressure increase connected with the constriction is assigned to the boundary layer which has just become turbulent. In the case of bodies with a retractable wheel, the cross-section can be reduced to the value required for strength, without any great concern. However, there should be a round transition into the cone end piece. It is more difficult to specify an optimum body contour for a wheel already installed, because the wheel drag is increased due to the constriction of the body contour.

Of course, these considerations can only be considered in an entirely new design. In an already-built aircraft, one has to reach a compromise. In a Ka-6 aircraft, for example, it is very worthwhile to make the body nose hermetic and smooth, but it would not make sense to change the ventilation, because there is a turbulent vortex at the discontinuity between the canopy and the body. It is also worthwhile to use round surfaces in front of and to the sides of a fixed wheel. According to wind-tunnel measurements, the drag coefficient of a half-retracted wheel for an aircraft with the dimensions of a Ka-6 is $c_w = 5.0 \times 10^{-4}$ without a cover. It is reduced to 3.8×10^{-4} if small round surfaces are used, and to 2×10^{-4} by means of a primitive outgoing flow cover, for which the initial cross-section is the cross-section of the wheel.

Finally, we would like to discuss antenna installation. Sometimes one finds antennas which are perpendicular to the body surface. Their drag is about as great as the drag of one-half of a control surface.

7. CONTROL SURFACES

For a control surface consisting of elevators and rudders, the profile shape should be selected according to the position of the rudder axis, so that transition occurs with certainty just ahead of the rudder. The rudder gaps must be carefully sealed, just as for the aileron. One usually uses horizontal tail assemblies with quite-thin profiles, with a relative thickness between 6 and 9%. At these small profile thicknesses, the profile shape has a negligible influence on the drag. However, there is an exception in the case of the pendulum rudder: here there can be transitions which are displaced far towards the back with certain profiles, for example, the series 66 NACA profiles. However, these shapes have to be somewhat modified so that the sudden transition to pressure increase at about 60% chord does not lead to separation of the laminar boundary layer. This design problem must not be overlooked. It is desirable to have a center of gravity position near the rotation axis, that is at 22-25% chord. The surface quality required to keep the flow laminar behind the axis of rotation requires an extremely light design. It does not make sense to sweep back the control surfaces, because sweepback has an unfavorable influence on keeping the flow laminar. The control surfaces should not start with the wedge-shaped extensions in the body, but should only have short round surfaces. The wedge-shaped fin displaces the turbulence of the body boundary layer outwards, because of its extreme sweepback, and the fraction of the surface of the control surface in a turbulent flow is unnecessarily increased.

The above discussion about several possibilities of reducing drag, is neither complete or new. In many places we had to give general recommendations instead of precise data. Nevertheless, a consequent application of these principles, which are relatively simple, and can be brought about without great technical complexities, will bring about a measurable performance increase.

Finally, we will again emphasize this possibility, which not only the designer has, but any glider pilot, who is concerned with his aircraft.

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