$\frac{k}{c} = \frac{0.35}{\sqrt{Re}} \sqrt{\frac{x}{c}}$. For example, the height k varies with $\sqrt{c}$, or for a taper of 0.5, k must be 30% smaller in the outer wing than in the inner wing. The values of k given for the flat plate form a very useful guide to the allowable roughness limits for wing sections whose boundary layers are generally 20 to 30% thinner than for the equivalent flat plates because of their negative pressure gradient. This means that the critical-roughness heights between the leading edge and the maximum section thickness are a little smaller than indicated in Figure 12. One is then dealing with lower limits which would, in the flat-plate case definitely not be "felt" by the boundary layer. For fuselage surfaces, that is surfaces with three-dimensional flows over them, the critical values are again a little lower than those given in Figure 12. The values in the case of the front part of the fuselage must be multiplied by a factor of 0.7 to 0.6.

The reason for this thinner boundary layer on the front part of the fuselage, in comparison to that on the flat plate, lies with the ever-growing periphery. The boundary layer encircling the body is subjected to continuous sideways thinning and thus has a lower streamwise rate of growth than that of the flat plate. Naturally the reverse is true of a contraction in the fuselage area; the boundary layer flows together and can become more than twice as thick as at the flat plate.

It is by no means true, as one sometimes hears, that a grease spot can lead to turbulence. On the contrary, rough sandpaper will often not exceed the critical roughness height. Naturally things are more critical in the immediate vicinity of the wing leading edge or the fuselage nose.

How does one find the roughness magnitude? In certain cases, obviously, by measurements. In practice the feel of the fingertips and the palm of the hand is quite sufficient. (One can test this with a piece of cellotape which is about .003" thick.) Roughness that can no longer be felt, will, in general, be far smaller than the critical roughness height.

* * *

In Figure 12 are also shown two lines which have nothing to do with laminar flow, but show the allowable roughness for a boundary layer that has become turbulent. Up to these roughness values and Reynolds Numbers the surface is considered "aerodynamically smooth." Greater roughness heights increase skin friction for turbulent boundary layers, for example, by about 20% when the roughness height is doubled. The values are, as in the laminar case, safe limits; for example, in the case of increasing pressure somewhat larger degrees of roughness are allowable. Figure 12 shows the strong influence of Reynolds Numbers: With a turbulent boundary layer the surface, apart from the first four inches, must be even smoother than for the laminar boundary layer.

The question as to what the allowable surface waviness is, can not be answered so explicitly. Probably there is no "allowable" waviness. Theoretical investigations have shown that for a sufficient number of waves, no matter how small the amplitude, separation of the laminar boundary layer always occurs. That transition should occur considerably earlier than in the case of a wave-free surface is thus not surprising.

Whereas single isolated waves occur frequently, it is unlikely that a regular system of waves should be built up on an actual surface. It is probable that a single wave whose amplitude is not greater than the critical roughness heights shown in Figure 12 will not influence the transition point. It is not beyond question that certain wave lengths are more dangerous than others through a form of resonance. This could be the case with wavelengths of 80 to 150 roughness heights. Early transition results first and foremost in a greater skin friction but, with certain unfavorable conditions such as with full ailerons applied in the outer wings, one also frequently obtains separation of the turbulent boundary layer which leads quickly to much greater drag. One should thus not only check the surface finish, but also the position of the transition points from flight tests. For example, one should obtain qualitatively similar curves to those shown in Figure 13 for the variation of transition point with incident x (or with C_L or with velocity v). If wind-tunnel data are available for the profile used one should ascertain that the wind-tunnel results have also been attained in flight, and if not, locate the differences. If the transition points do agree one can rest assured that the drag values are of the same magnitude as those obtained from the tunnel tests.

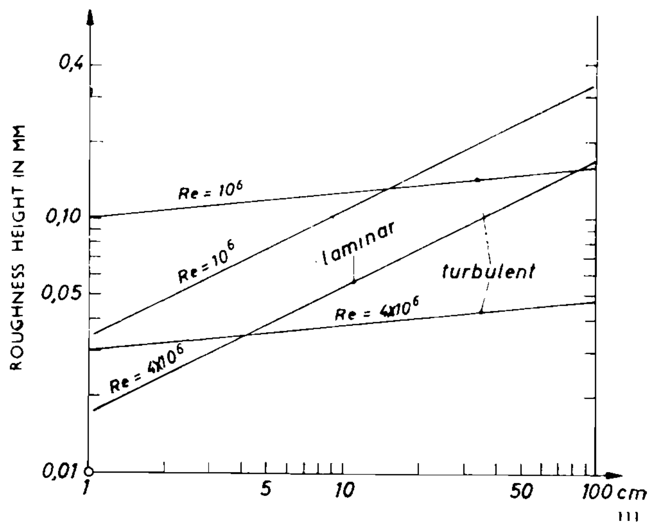

Fig. 12

In flight, however, it is not as simple to deduce transition as in wind tunnels where one can with the aid of a simple microphone, easily differentiate the quiet whistle of the laminar boundary layer from the rough roar which characterizes turbulent flow. One should be able to observe at least 20 positions in each semi-span with built-in pressure probes. Because of their sensitivity to other acoustical signals microphones are not very suitable for listening to the boundary layer. The same can be said of pitot tubes because of the low total pressure. My colleague, Dipl.-Phys. D. Althaus, has, for this reason, developed a simple and certain method for observing transition points on sailplanes on which he will report shortly.

FLAPS AND AIR BRAKES

After this diversion about the nature and control of laminar flows, here are a few more comments about flaps and air brakes. Normally a laminar boundary layer becomes turbulent at the latest in the region of the brakes. Either the brakes do not fit flush when re-