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SPECULATIVE CONSIDERATION ON HIGH-FREQUENCY INSTABILITY OF THE LAMINAR BOUNDARY LAYER AND ITS EFFECT ON THE DESIGN OF STABILIZING COATINGS

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UNITED STATES AIR FORCE PROJECT RAND

The RAND Corporation
SANTA MONICA • CALIFORNIA

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PREFACE

This Memorandum reports on one facet of a potentially important advance in minimizing skin-friction drag of both aircraft and hydrocraft.

Several features of the distributed-damping method of laminar-flow control are of particular interest for potential vehicular applications: no pumps, associated power sources, or ducts are required within the vehicle; and the stabilizing surface coating applied to the vehicle has a smooth, impermeable surface that is not subject to clogging.

This Memorandum summarizes the author's views on a means of effecting a substantial advance in the distributed-damping boundary-layer-stabilization technology, based on his previous experimental work and on recent boundary-layer-transition measurements of others. The prior status of that technology was summarized in a previous Memorandum by the same author, RM-3018-PR, Material Requirements for Boundary-Layer Stabilizing Coatings--Water Applications.

SUMMARY AND CONCLUSIONS

This Memorandum discusses a possible high-frequency instability of the laminar boundary layer, on the basis of limited theoretical work and experimental evidence. In particular, recent experimental data indicate that the final transition of the laminar boundary layer is caused by a fast-developing vortex street.

It is concluded that:

1. Recent theoretical work indicates the possibility of a high-frequency instability of the laminar boundary layer.

2. Recent experimental findings provide evidence for the existence of a high-frequency instability of the laminar boundary layer.

3. The critical frequency of the experimentally indicated high-frequency instability is approximately 40 per cent of the free-stream velocity divided by the laminar-boundary-layer thickness or about 25 times the most critical frequency of the Tollmien-Schlichting waves.

4. The wave length of the high-frequency instability is about 1.9 times the laminar-boundary-layer thickness or approximately 1/8 the wave length of the most critical Tollmien-Schlichting waves.

5. The eddies resulting from the high-frequency instability are spaced much closer to the surface than to each other, which makes the damping of the high-frequency instability of the laminar boundary layer by an appropriate stabilizing coating a promising possibility.

CONTENTS

I. INTRODUCTION

Reference 1 has presented evidence that stabilizing coatings, based on the principle of distributed damping, can stabilize the laminar boundary layer under conditions in which it would normally be unstable. The increase in transition Reynolds number achieved prior to 1958 was demonstrated by the author at the David Taylor Model Basin in January 1959. Although the results have not been published, a 40 per cent friction-drag reduction on slender models 4 ft in length was measured at that time. This represented an increase in the transition Reynolds number of approximately 150 per cent and thus apparently confirmed the soundness of the basic approach.

The stabilizing coating used for the 1959 demonstration was designed on the basis of the Tollmien-Schlichting theory(2) of the instability of the laminar boundary layer on a rigid surface. The Tollmien-Schlichting theory predicted the development of unstable waves in the laminar boundary layer. Their most critical wave length is comparatively long, approximately 15 times the thickness of the laminar boundary layer. The waves propagate downstream comparatively slowly, at approximately one-quarter the free-stream velocity. As a result of the long wave length and the low propagational speed, the pressure oscillations, induced at the surface by the passage of the Tollmien-Schlichting waves, are of comparatively low frequency. The stabilizing coating that was demonstrated in 1959 had been specifically designed to damp this particular type of disturbance--namely, the Tollmien-Schlichting waves.

The Tollmien-Schlichting theory is based on the assumption of ideal flow conditions: i.e., negligible ambient turbulence and a surface that is free from waviness, protuberances, and roughness. The Tollmien-Schlichting theory was experimentally verified only after ideal flow conditions had been artificially realized in specially designed wind tunnels. It is reported(3) that even at the low ambient-turbulence level of 0.2 per cent, the Tollmien-Schlichting waves are no longer detectable, and that above this level the degree and scale of the ambient turbulence control the transition from laminar to turbulent flow.

The ambient turbulence of an operating medium is beyond one's control. Its level is determined by the environmental conditions. It often exceeds the limit[3] of 0.2 per cent that was determined from measurements in boundary-layer flow over a flat plate. It is generally known that the limiting ambient-turbulence level is even lower for laminar profiles, e.g., the laminar-flow airfoil sections of twenty years ago. Systematic measurements of the turbulence-sensitivity of laminar profiles cannot be found in the literature. In addition, the possibility exists that once the Tollmien-Schlichting waves are damped, for instance, by an appropriate stabilizing coating, still smaller amounts of ambient turbulence may be controlling the transition.

The great sensitivity of the laminar boundary layer to ambient turbulence, as well as the only partially effective coatings designed on the basis of the Tollmien-Schlichting theory, suggested the possibility that frequency ranges other than the Tollmien-Schlichting frequency range of instability might exist in which the laminar boundary layer responds with unstable fluctuations. Since the Tollmien-Schlichting waves cover the low-frequency range of the laminar boundary layer, it was anticipated that a second instability, if existing, would be found in the high-frequency range. Thus a literature search was undertaken in order to find theoretical and/or experimental evidence of the existence of a high-frequency instability of the laminar boundary layer. Such evidence does indeed exist, as discussed in Section II.

While further theoretical work is needed to clarify the underlying phenomena, the practical development of stabilizing coatings does not have to wait for the conclusion of this theoretical work. Just as the first stabilizing coating could be designed once the critical wave length and the critical frequency in the low-frequency range were known, improved coatings can be designed and systematically tested once approximate information about the wave length and frequency of the most critical high-frequency instability is available.

II. EVIDENCE FOR THE EXISTENCE OF A HIGH-FREQUENCY INSTABILITY OF THE LAMINAR BOUNDARY LAYER

The theory of the laminar boundary layer has not yet progressed to the point where it can provide the desired information on the wave length and frequency of the most critical high-frequency instability of the laminar boundary layer. A recent paper(4) states: "In summary, the existence of a high-frequency boundary layer flow affecting the whole basic boundary layer domain is (theoretically) indicated." Future theoretical work will without doubt clarify the mechnnism of any possible high-frequency instability.

The most valuable experimental information concerning the high-frequency instability hypothesis was found in Ref. 5 and, recently, in Ref. 6. The experiments were undertaken as an extension of the verification of the Tollmien-Schlichting theory and were intended to clarify the transition from Tollmien-Schlichting waves into fully developed turbulence. Figure 1 shows an essential result of Ref. 5, namely, the speed oscillations in the boundary layer during the transition from waviness into turbulence. Forced Tollmien-Schlichting waves of critical frequency and stepwise-increased amplitude were generated in the laminar boundary layer with the aid of the ribbon technique. In the first oscillogram (top oscillogram in Fig. 1) the wave amplitude is small and nothing unusual happens. As the wave amplitude is increased (second oscillogram in Fig. 1) sudden spikes appear. They grow in intensity and frequency of occurrence as the wave amplitude is further increased (third oscillogram in Fig. 1). Attention must be paid to the details: e.g., in the third oscillogram, the spikes still have a regular spacing and appear only at the time the speed in the wave is decreasing. The regular spacing and high intensity of the spikes suggest the passage of a regular vortex pattern with a well-defined frequency and wave length similar to that of a Karman vortex street. The first occurrence of the vortices, at the time the speed in the wave decreases, seems to indicate that the instantaneously positive or adverse pressure gradient due to the wave motion is a necessary condition for the sudden appearance of the vortices. The sudden and strong occurrence of the vortices

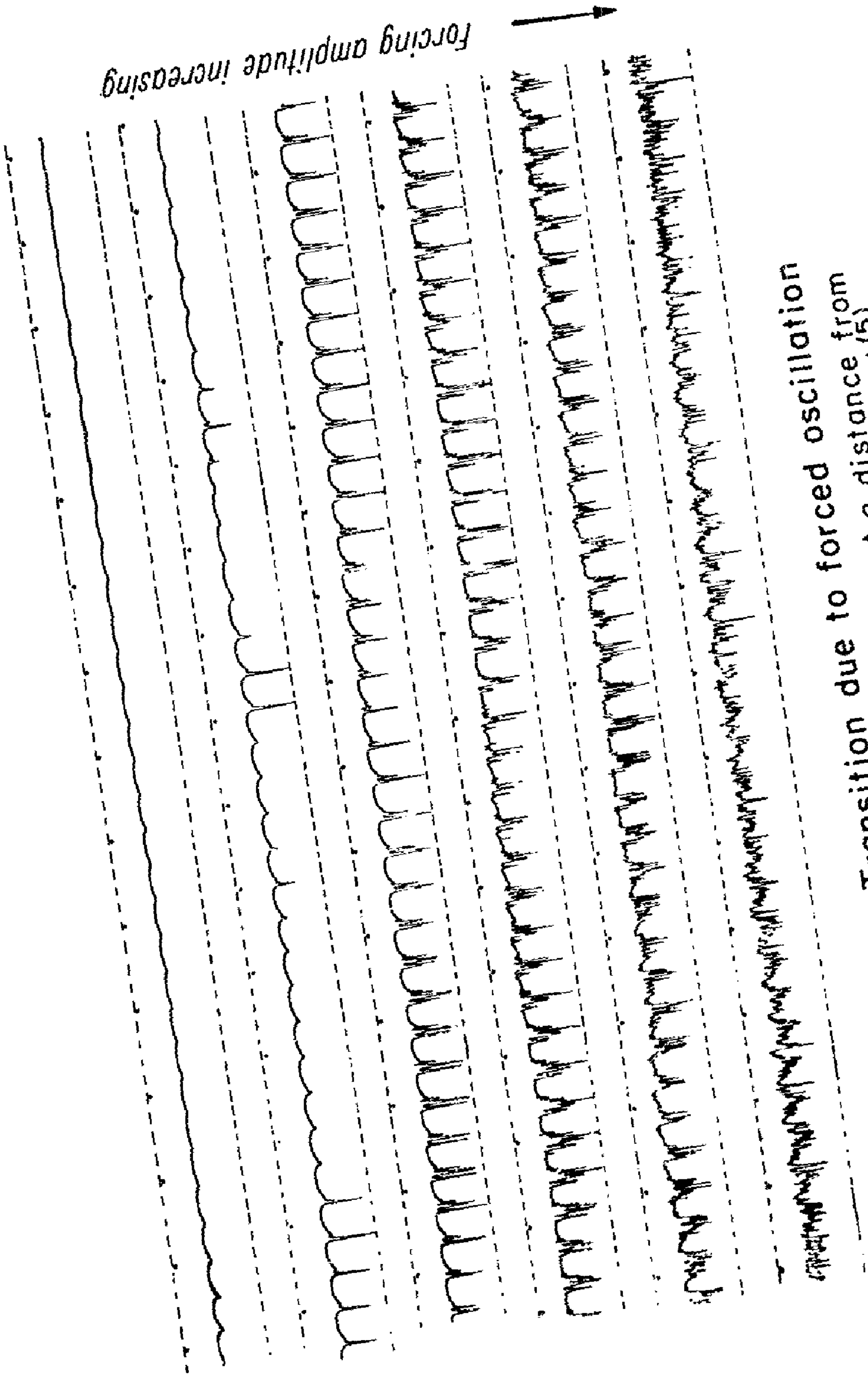

Fig. 1 — Transition due to forced oscillation
(Speed oscillations recorded at a distance from the wall of 0.6 boundary-layer thickness)(5)

indicates a strong instability at their particular frequency and wave length once the stage is set by an instantaneously positive or adverse pressure gradient at the point of observation.

Figure 1 seems to indicate the existence of a high-frequency instability of the laminar boundary layer. This instability seems to require a small positive or adverse pressure gradient for its sudden appearance. Reference 3 assumed that the locally adverse pressure gradient due to ambient turbulence causes local flow separation and thus starts the transition into fully developed turbulence. It is known that flow separation develops slowly and thus may not be capable of following the quick changes in pressure gradient that are due to the passage of ambient turbulence. On the other hand, Fig. 1 indicates that the high-frequency instability of the boundary layer springs up very suddenly and therefore is well capable of responding to sudden changes of the pressure gradient. Thus the possibility exists that the transition due to ambient turbulence might be caused not by the local flow separation but by the high-frequency instability of the boundary layer. The high-frequency instability of the boundary layer might represent the connecting link between many kinds of flow disturbances, such as Tollmien-Schlichting waves, ambient turbulence, or surface waviness and the actual transition into fully developed turbulence, since all these disturbances can cause a locally adverse pressure gradient. When the Tollmien-Schlichting waves are damped by a favorable pressure gradient or by the existing type of stabilizing coatings, it might be especially promising to damp the high-frequency instability in order to reduce the detrimental effect of weak ambient turbulence on the transition Reynolds number.

III. ESTIMATED FREQUENCY AND WAVE LENGTH OF THE HIGH-FREQUENCY INSTABILITY

An estimate of the frequency of the high-frequency instability can be made from Fig. 1. The intervals between the timing dots in Fig. 1 are 1/60 sec. From the second oscillogram, it can be noted that only single spikes appear and at intervals of about 1/120 sec. In the third oscillogram, groups of spikes appear and their frequency within the group can be determined as being close to 1200 cps. The free-stream velocity was 50 ft/sec and the distance from the leading edge was 4 ft during the recording shown in Fig. 1. Thus

Reynolds number = 1.4×10^6

Boundary-layer thickness, $\delta = 5.3 \dfrac{L}{\sqrt{R}} = 5.3 \dfrac{4}{\sqrt{1.4 \times 10^6}} = 0.018$ ft

When assuming that the frequency is proportional to the free-stream velocity and inversely proportional to the boundary-layer thickness, as it is in a Karman vortex street, the frequency of the high-frequency instability appears to be

$$\omega_{(H.FR.)} = 1200 \frac{U_o}{50} \frac{0.018}{\delta} = 0.43 \frac{U_o}{\delta}$$

or approximately 25 times the frequency of the most critical Tollmien-Schlichting waves.

The wave length can be derived only indirectly and very approximately from Ref. 5, since no attempt was made to measure this information. Figure 2 shows the speed distribution in the undisturbed laminar boundary layer as a solid-line curve and the speed distribution in the wave at the time the speed in the wave is at a minimum as a short-dash curve. The latter curve is taken from Ref. 7. Reference 5 mentions that the greatest relative speed decrease in the spike was measured at 60 per cent of the boundary-layer thickness and that the relative change in speed due to the spikes became insignificant at 5 and 120 per cent of the boundary-layer thickness. Based on this preliminary information, an

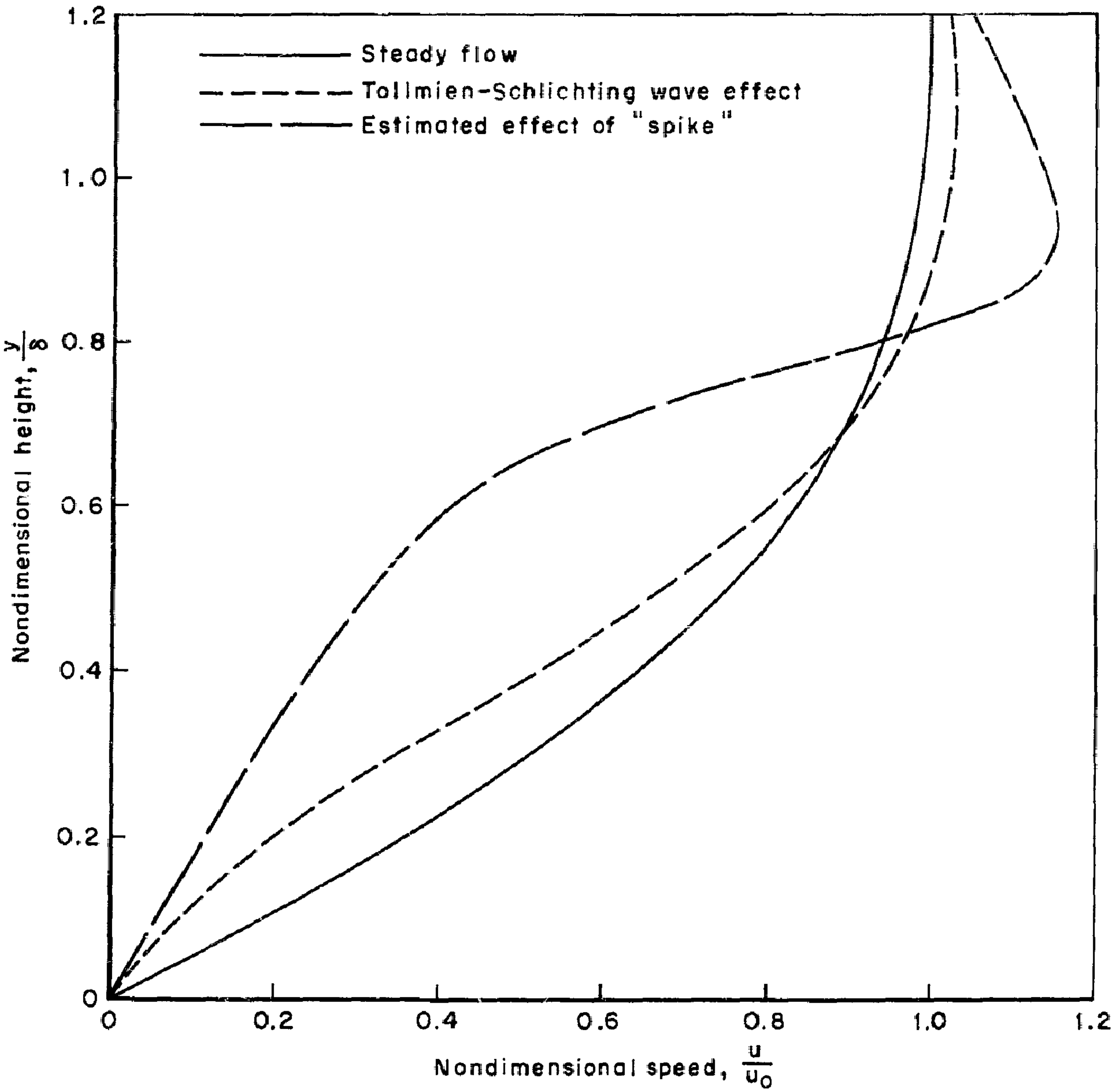

Fig. 2—Speed distribution in the laminar boundary layer on a flat plate

estimated speed distribution in the boundary layer at the time of the passage of the spike is plotted on Fig. 2 as the long-dash curve. Figure 2 indicates that the center of the vortex causing the spike should be located at 80 per cent of the boundary-layer thickness. Thus, the vortices should travel at about 95 per cent of the free-stream velocity, or approximately four times faster than the Tollmien-Schlichting waves. Since the wave length is

$$\lambda = \frac{U_{\text{Propagational}}}{\text{Freq.}}$$

the wave length of the high-frequency instability can be estimated as

$$\lambda_{(\text{H.FR.})} = \frac{0.95\ U_o\ \delta}{0.43\ U_o} = 2.2\ \delta$$

Reference 6, which has become available since the above estimates of wave length and frequency were made, has provided improved information on the high-frequency instability of the laminar boundary layer. According to Ref. 6, the frequency is

$$\omega_{(\text{H.FR.})} = 0.36\ \frac{U_o}{\delta}$$

which is 20 per cent less than that deduced from Ref. 5.

According to Ref. 7, the spacing of the eddies or the wave length is

$$\lambda_{(\text{H.FR.})} = 1.9\ \delta$$

which is 15 per cent less than was anticipated on the basis of the preliminary information given in Ref. 5.

Based on Ref. 6, Fig. 3 shows the flow pattern of the high-frequency instability at its origin. The fact that the eddies are much closer to the surface than to each other is considered to be important evidence that the fast-propagating eddies strongly affect the pressure distribution at the surface and thus make possible an effective damping of the high-frequency instability by a properly designed stabilizing coating.* Such a coating, designed to introduce positive damping of the high-frequency as well as the low-frequency instability of the boundary layer, can be expected to have a performance superior to that of existing coatings that are designed to damp only the low-frequency instability.

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*Very recently, Ref. 8 has shown that the passage of the high-frequency eddies causes strong pressure disturbances at the surface.

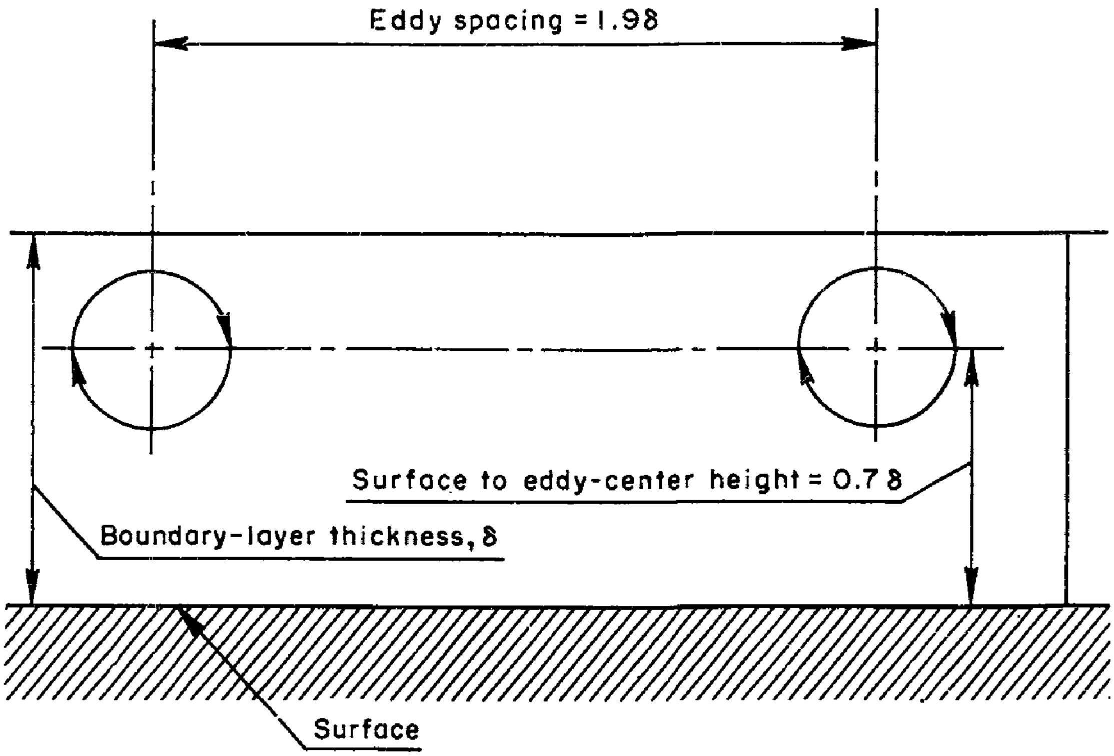

Fig. 3 — Flow pattern of the high-frequency instability at its origin in the laminar boundary layer

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