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DEVELOPMENT OF PERTURBATIONS IN THE BOUNDARY LAYER

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16. Abstract

The article discusses the transition of laminar flows into turbulent flows in a boundary layer. Examined herein are the individual aspects of the transition process, observed under controllable model conditions.
This article is basically devoted to one of the aspects of this problem, namely the development or excitation of the natural oscillations in the boundary layer, the so-called "Tollmin-Schlichting waves". Three types of excitation of these waves are considered: a) distributed generation throughout the boundary layer; b) generation in the vicinity of the forward edge of a model, having either a sharp edge or an edge with a large radius or curvature, and c) generation in a developed boundary layer by means of a focused effect.

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DEVELOPMENT OF PERTURBATIONS IN THE BOUNDARY LAYER

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One of the important, and heretofore unsolved questions of aerohydrodynamics is the question of the transition of laminar flows into turbulent flows. Numerous theoretical and experimental studies of the various aspects of this phenomenon have found reflection both in special monographs or parts of monographs [1]-[8], and in survey articles [9]-[17]. Examined in the present survey are individual aspects of the transition process in the boundary layer, observed under controllable model conditions. Thus, there is no detailed analysis here of the numerous data on the so-called "natural" transition, although the authors of the present survey turn to some of them out of necessity, in order to show how, under "natural" conditions, the characteristic processes, which lead to transition under "model conditions", are manifested. /4*

During the study of the process of transition of a laminar flow into a turbulent flow in boundary layers, when the external perturbations are minor, three problems may be singled out at the present time:

I. The development or excitation of the natural oscillations of the boundary layer, the so-called Tollmin-Schlichting waves;

II. The linear development of Tollmin-Schlichting waves, when interaction between waves of various frequencies is absent;

III. The nonlinear development and interaction of waves, three-dimensional effects, as a result of which there occurs final destruction of the laminar conditions of the flow, and transition to turbulence.

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Examined in the present survey are the results of studies on the first aspect. The fact that turbulence in the boundary layer is a result of the development of minor perturbations, the Tollmin-Schlichting waves, was established during carrying out of the experiments, in an aerodynamic tube with a very low degree of turbulence of the flow [18]. Subsequent experiments in low-turbulence aerodynamic tubes, for the determination of the so-called "transition point" in the boundary layer on a flat plate, gave a considerable divergence in the results [19] (see Fig. 1). /5
There are no doubts that the transition in these experiments occured via the Tollmin-Schlichting mechanism. The difference in the results is a result of the conditions in different aerodynamic tubes and the characteristics of the models, and, more precisely, the difference in the results is a result of the difference in the nature and degree of excitation of the Tollmin-Schlichting waves in different experiments. Unfortunately, in the experiments on the study of the "natural" transition in the boundary layers, the external conditions were studied far from sufficiently, and it was therefore not always possible to pick out the factors which critically affect the results. It was precisely the substantial dependence of the transition on the external conditions and on minor external perturbations which posed the problem of "receptivity" of the boundary layer to external perturbations. This problem consists of how, by means of which mechanisms, the various minor external perturbations (turbulence of the basic flow, acoustic perturbations, vibrations of the models being flowed around, surface roughness, and so on) excite the natural oscillations of the boundary layer.

The problem of "receptivity" of the boundary layer to external perturbations (English term "receptivity") was clearly formulated by M. Morkovin ten years ago. Definite results on its solution, which will be discussed below, have been obtained in very recent years.

In speaking of the excitation of Tollmin-Schlichting waves in the boundary layer with small amplitudes of the external perturbations, one should evidently distinguish the following means of their excitation by the external perturbations:

a) distributed generation of Tollmin-Schlichting waves throughout the boundary layer;

b) generation of Tollmin-Schlichting waves in the vicinity of the forward edge of the model, in this case making a distinction between a sharp forward edge, and a forward edge with a large radius of curvature;

c) generation of Tollmin-Schlichting waves in a developed boundary layer by means of a focused effect.

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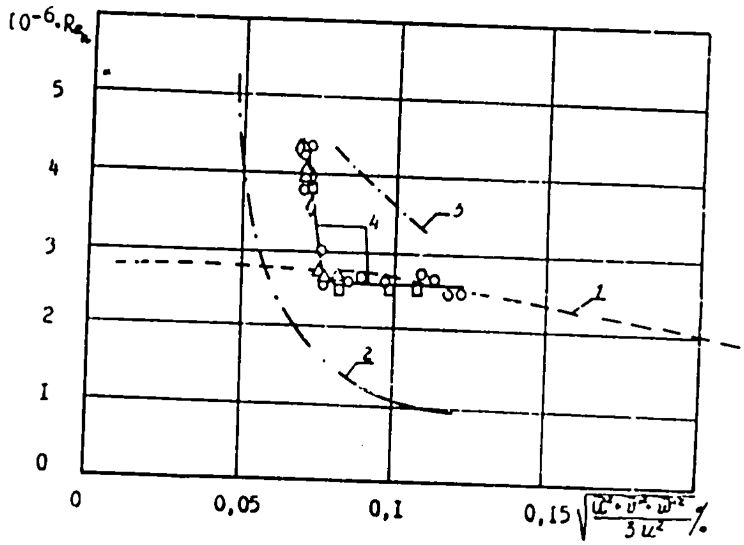


Fig. 1. Effect of degree of turbulence of approach stream on location of "natural" transition [19]. 1—Schubauer and Skramstad; 2—Spangler and Wells; 3—V. M. Filippov; 4—N. F. Polyakov.

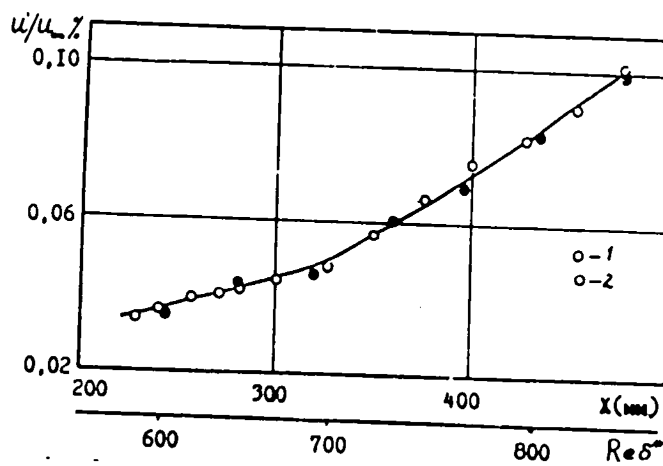


Fig. 2. Dependence of amplitude of perturbation on the Reynolds number: 1—with sound, 2—without sound.

Distributed (Continuous) Generation of Tollmin-Schlichting Waves in Boundary Layer /7

One of the key questions of the "receptivity" of the boundary layer is the question of how the Tollmin-Schlichting waves, which have a propagation rate in the region of instability equal to roughly 0.4 the rate of the external flow, are excited by the external turbulence, which propagates, on the average, at the rate of the flow, or by acoustic perturbations, propagated at the speed of sound, and whether they are excited or not. This question naturally occurs in view of the known experimental facts [19]-[25] of the substantial effect of the indicated external influences on the Reynolds number of the transition, under conditions when the transition takes place via the Tollmin-Schlichting mechanism. There are also experimental observations which indicate the definite effect of the longitudinal sound field on the development of waves in the boundary layer, although the nature of this effect has not been studied [23], [24]. But if there is a connection between the indicated perturbations (theoretical models may be constructed, which will be discussed below), then how strong is it?

Experimental studies of the question of the continuous generation of Tollmin-Schlichting waves under controllable conditions have been carried out in [27] and [28]. The experiments were carried out on a plate with a sufficiently sharp forward edge.

Studied in the first series of experiments was the development of Tollmin-Schlichting waves, excited artificially in the boundary layer on the flat plate by a vibrating band, in the absence and in the presence of a longitudinal sound field, in a broad range of frequencies of the Tollmin-Schlichting waves and the superimposed sound. In this case, special attention was given to the separation of the signal into its acoustic and vortical components. The continuous generation of Tollmin-Schlichting waves, in the given experiments, would mean a continuous supply of energy to the developing waves, and should be expressed in a change in the coefficients of intensification of the perturbations and other characteristics of stability of the boundary layer. However, within the limits of accuracy of the experiment, we observed no effect whatsoever of the longitudinal sound field on the characteristics of development of perturbations in the boundary layer (Fig. 2).

Carried out in the next series of experiments were measurements of the structure of the laminar boundary layer in a longitudinal sound field in the absence of "artificial" perturbations (i.e., in the absence of a vibrating band). It was found that, under these conditions in the boundary layer, waves develop from the vicinity of the forward edge of the model, which are identical in all their characteristics to the natural oscillations of a stationary boundary layer (Fig. 3). In these tests, with cutting-off of the sound, Tollmin-Schlichting waves were not observed in the range of the studied Reynolds numbers, in view of the insignificance of their amplitudes. From the described two series of experiments, one should conclude that the distributed generation of Tollmin-Schlichting waves in the boundary layer by a longitudinal sound field, if it exists, is very insignificant; a considerably stronger effect is the concentrated generation of Tollmin-Schlichting waves in the vicinity of the forward edge of the model, which leads to a substantial increase in their initial amplitude. /8

The only attempt at a similar experimental study, known to the authors, was undertaken by Shapiro [29]. The obtained results showed that it was as if the coefficients of intensification of the perturbations vary under the effect of the longitudinal sound field. However, upon closer examination of the obtained data (the author described the conditions of the experiments in rather great detail), it is revealed that this is not so. Actually, study [29] rather graphically demonstrated the procedural difficulties of carrying out this type of experiments, which the author did not succeed in overcoming, and, as a result, erroneous conclusions were drawn. Thus, in Shapiro's study, the summary signal from the gauge of the thermal flowmeter was brought about by perturbation of three sorts: acoustic pulsations, vibrations of the coordinate spacer, the plate and the gauge (under the effect of the sound), and the Tollmin-Schlichting waves. Separation of the signals from these three types of perturbations of identical frequency, but different nature, was not carried out (in contrast, for example, to study [27]). But the summary signal was identified with the signal evoked by the Tollmin-Schlichting wave. The superposition of the three indicated types of signals lead to spatial pulsations, the nature of which was not understood by the author of study [29]. As a result, the author, taking acoustic or vibrational perturbations for the waves of the boundary layer in a number of cases, arrived at absurd results of the type of a "standing Tollmin-Schlichting wave". The effects observed in study [29] in no way change the conclusions of study [27], and may be explained all the more easily with consideration of the true nature of the signal at the output of the thermal flowmeter, under the conditions of an acoustic field of great intensity.

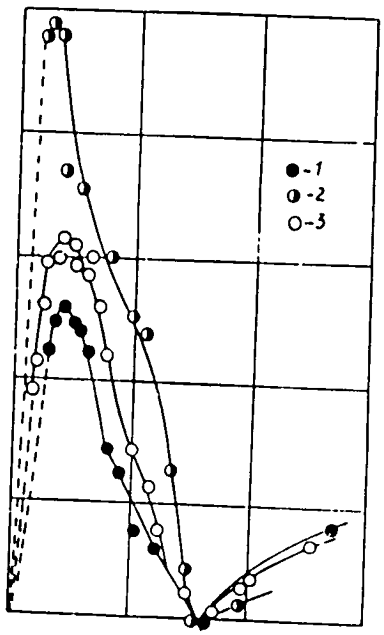
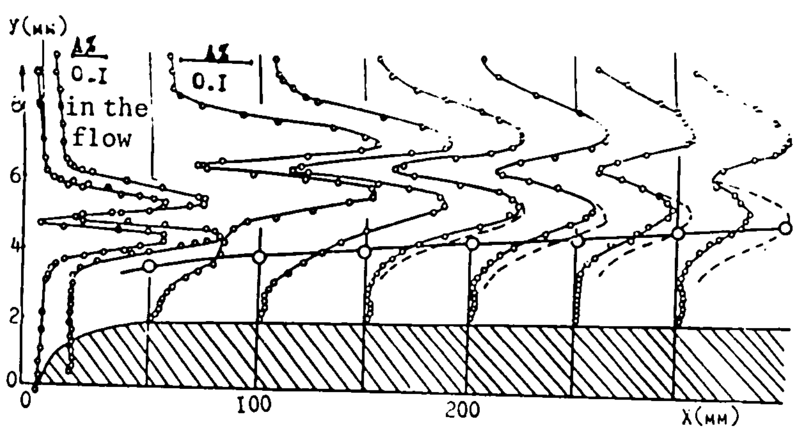


Fig. 3. Profiles of vortical perturbations induced in the boundary layer. /9

1—by sound waves
2—by vibrations of the plate
3—by a vibrating band.

Fig. 4. Change in pulsation component of rate for various cross-sections downstream.



Noted in the process of the experiments in study [27] was the presence of vibrations of the plate with the very same frequency as the applied acoustic field. With induced mechanical vibration of the plate, in the absence of an acoustic field, with amplitudes of the vibrations under the effect of sound, Tollmin-Schlichting waves were recorded in the boundary layer with the very same amplitudes as with the presence of a sound field. /10

Thus, the results of study [27] indicate that continuous generation of Tollmin-Schlichting waves in the boundary layer is either absent, or is negligibly small, with the effect of a longitudinal acoustic field on the boundary layer, or with the presence of vibrations of the rigid surface. The basic factor under these conditions is the concentrated generation of Tollmin-Schlichting waves in the vicinity of the forward edge of the plate.

It should be noted, however, that, with certain properties of the material of the surface being flowed around, a substantial change is possible in the characteristics of stability of the boundary layer, i.e., both continuous addition of energy to the Tollmin-Schlichting waves, as well as other types of waves, and also their deformation, are possible. This special case of "pliable" surfaces will not be examined here.

The measurement of the spectral composition of the perturbations prior to destruction of the laminar boundary layer, with the application of longitudinal acoustic perturbations, was carried out by N. F. Polyakov [30], [31]. The author recorded the appearance of hydrodynamic waves with the application of a sound field, and, in [31], put forth a hypothesis on the existence of resonances between the acoustic field and the natural oscillations of the boundary layer, i.e., on the distributed generation of hydrodynamic waves. However, practically all of the facts observed in these experiments may also be explained from the position of the generation of Tollmin-Schlichting waves in the vicinity of the forward edge.

Studies [32]-[34] are devoted to the theory of the examined question. In [32], the problem of the development of Tollmin-Schlichting waves in a noncompressed oscillating boundary layer is solved in a complex nonstationary posing of the problem, and the absence of the effect of longitudinal oscillations of the flow on the characteristics of stability of the boundary layer is obtained in full accordance with the results of the experiments in study [27], with small amplitudes of the sound. Analysis of the linearized compressible Navier-Stokes equations, undertaken in [33], showed that a connection exists in the boundary layer between the acoustic (non-vortical) and hydrodynamic (vortical) perturbations. But, according to this study, although generation of the /11
Tollmin-Schlichting waves takes place throughout the boundary layer with the given acoustic field, its intensity depends considerably on the thickness of the boundary layer, and is stronger in the vicinity of the forward edge of the plate. Specific calculations, which would show how strong this mechanism of generation of the T-Sh (Tollmin-Schlichting) waves is, are absent. At the present time, there are no experimental data on that account. The possibility of a connection between the hydrodynamic and acoustic waves is indicated in [34], [35], but there are no concrete results.

The possibility of distributed generation of T-Sh waves in the boundary layer by external vortical perturbations was studied experimentally in [28]. Perturbations of fixed frequencies were excited in the free flow prior to the plate by a vibrating band, so that their basic portion interacted with the boundary layer, bypassing the vicinity of the forward edge (Fig. 4). Measurements showed that, in this case, any appreciable generation of T-Sh waves in the boundary layer is absent, and external perturbations in it are sharply attenuated along the direction toward the wall. The results of the experiments are found to be in qualitative accordance with the results of the study of Rogler and Reshotko [36], in which the interaction of a system of vortices of low intensity, propagating at the rate of the free flow, with the boundary layer is theoretically studied. In [37], on the basis of nonviscous analysis, Rogler showed the principal possibility of the generation of T-Sh waves in a boundary layer of a different type by external vortical (and nonvortical) perturbations. The subsequent study of Rogler [38] showed that this process is stronger in the vicinity of the forward edge of the plate.

Generation of Tollmin-Schlichting Waves in the Vicinity of the Forward Edge

a) Sharp forward edge.

Experimental studies of the process of transformation of vortical perturbations of an approach stream into natural oscillations of the boundary layer (T-Sh waves), which takes place in the vicinity of a sharp forward edge of the plate ($\tau \ll \lambda$), are carried out in study [28]. External perturbations of fixed frequencies were excited upstream from the forward edge of a vibrating band, and the measurements were carried out with a single-filament thermal flowmeter gauge. The picture of the transformation is presented in Figure 5. A characteristic detail is the strongly localized

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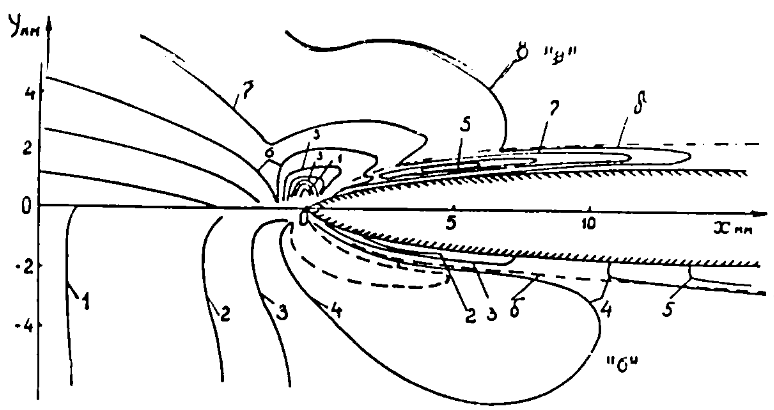

Fig. 5. Lines of equal intensity ("a") and equal phase ("b") of longitudinal component of velocity pulsations.

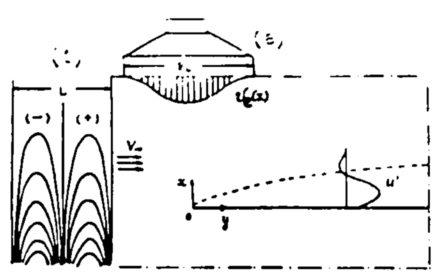

Fig. 6. Theoretical simulation of generation of T-Sh waves in the region of the forward edge:
a) Lateral standing wave; b) Traveling wave.

(near the forward edge) region of increased intensity of the longitudinal component of the velocity pulsations. In this very same region, there also occurs a phase discontinuity. Observed downstream from this region is a traveling T-Sh wave, with a frequency equal to the frequency of the external perturbation, the rate of propagation of which, obtained from phase measurements, was equal to ~0.4 the rate of the free flow. The discontinuity in the intensity, with a constant radius of the forward edge, depends substantially (inversely proportionally) on the frequency of the approach perturbation. /13

The presence of a lateral (with respect to the forward edge) component of the velocity of the external perturbation plays a very large role in the process of generation of the T-Sh waves. When the band was mounted so that this component of the perturbation was absent, the field of the flow at the root differed from that depicted in Figure 5, and the T-Sh wave was not observed in the boundary layer. Generation of T-Sh waves took place with the exposure of the forward edge to lateral sound waves in the experiments of study [39]. In the experiments described above, with a longitudinal acoustic field [27], the generation of T-Sh waves took place because of vibrations of the forward edge of the plate in a lateral direction. The decisive role of the lateral component of the velocity of the external perturbation in the process of generation of the T-Sh waves, in the vicinity of the forward edge of the plate, is corroborated by the calculations in [40]. The calculations are based on the numerical integration of the linearized Navier-Stokes equations for the steady-state periodic (with a given frequency $\overline{\beta}$) perturbing movement $\psi'(x,y,t) = \varphi(x,y)e^{-i\beta t}$, $\omega'(x,y,t) = \zeta(x,y)e^{-i\beta t}$

$$-i\beta\zeta + \frac{\partial\Psi}{\partial y}\frac{\partial\zeta}{\partial x} - \frac{\partial\Psi}{\partial x}\frac{\partial\zeta}{\partial y} - \frac{\partial\Omega}{\partial y}\frac{\partial\varphi}{\partial x} + \frac{\partial\Omega}{\partial x}\frac{\partial\varphi}{\partial y} = \frac{1}{Re}\frac{\partial^2\zeta}{\partial x^2} + \frac{\partial^2\zeta}{\partial y^2}$$

$$\zeta = \frac{1}{Re}\frac{\partial^2\varphi}{\partial x^2} + \frac{\partial^2\varphi}{\partial y^2}$$

The unperturbed flow (Ψ,Ω) is determined from the solution of the complete Navier-Stokes equations. Two types of external perturbations are examined.

The lateral standing wave

$$U(x,t) = U_e(x) e^{ipt}$$

concentrated in the region of the forward edge of the plate (Fig. 6,a), qualitatively simulates both the exposure to acoustic waves

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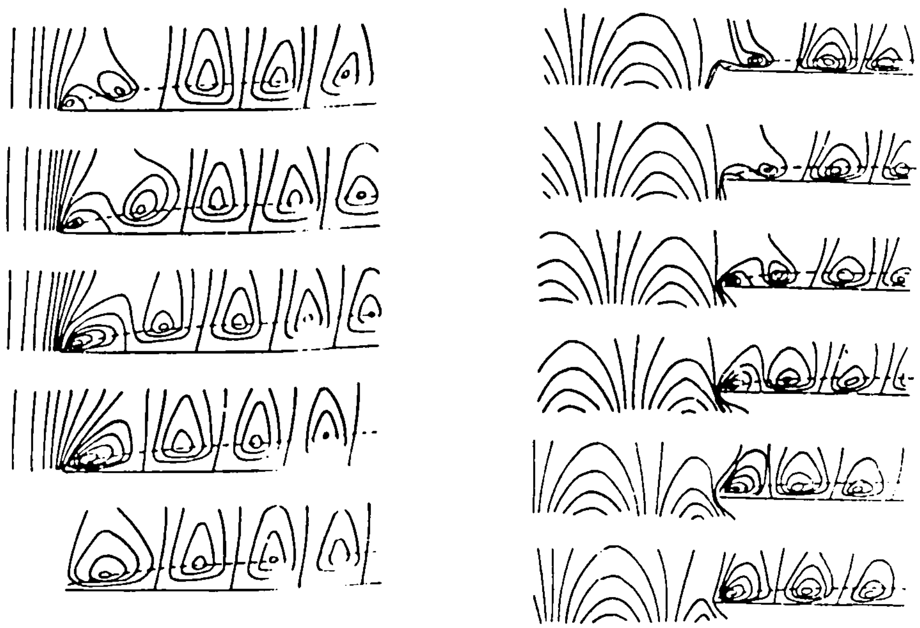

"a" "б"

Fig. 7. Generation of Tollmin-Schlichting waves on the forward edge of a plate with different types of perturbations in the theory: a) Lateral standing wave; b) Traveling wave.

of great length and small vibrations of the forward edge. /15

The traveling wave $\Psi'(x,y,t) = e^{-\frac{y}{\sqrt{\alpha}}} e^{i\alpha(x-t)}$, propagating with the local rate of the flow and approaching the forward edge of the plate (Fig. 6,b), approximates with great accuracy the external perturbations of the Karman path type, created in experiments in [28].

These expressions for standing and traveling waves were utilized during the calculations as the corresponding boundary value conditions. Shown in Figure 7 are the different phases of generation of T-Sh waves on the forward edge in numerical calculations for both cases of external perturbations. Given in Figure 8 are the results of numerical calculations for the case of a traveling wave (upper part of figure), and also the results of the corresponding experimental measurements. Comparison of these results indicates their excellent agreement.

b) Forward edge which has a rather large radius of curvature.

In the case of a forward edge, which has a rather large radius of curvature, the question of the transformation of external perturbations into Tollmin-Schlichting waves remains completely open, in view of the extremely complex, and still unclear nature of the flow. As early as the 1920's, in the experiments of Piercy and Richardson [41], "anomalous" behavior of a flow close to the forward critical point was observed. In their measurements, using a thermal flowmeter, of the distribution of the velocity and perturbations of the velocity on a round cylinder and profiles, it was noted that the amplitudes of the velocity perturbations in direct proximity in front of the front point increase considerably. Later visual studies [42]-[44], with turbulent flow-around of round cylinders, located obliquely and perpendicular to the flow, showed the presence of stationary paired vortices of different signs, as a result of which the boundary layer, which forms on the surface of the body being flowed around, takes on a more or less pronounced three-dimensional structure, which differs from the unperturbed flow-around. This indicates that, in this case, we should examine the three-dimensional problem of flow-around of a body, both for an average flow and for perturbations.

Attempts at the theoretical description of this phenomenon have been undertaken in studies [45]-[48] and others. In this case, it is necessary to note that a common point of view is absent. A detailed critical survey of the state of this question was recently made by Morkovin [49].

<u>Generation of Tollmin-Schlichting Waves in a Developed Boundary Layer by Means of a Concentrated Effect</u> /17

If the distributed generation of Tollmin-Schlichting waves in a boundary layer on a rigid plate is theoretically possible (although

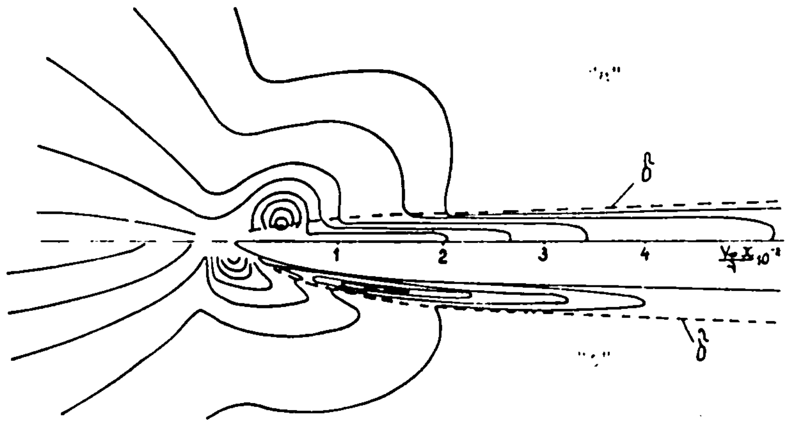

Fig. 8. Distribution of lines of equal root-mean-square intensity of longitudinal component of velocity pulsations in the region of the forward edge. Upper half—("a") theory, lower half—("b") experiment.

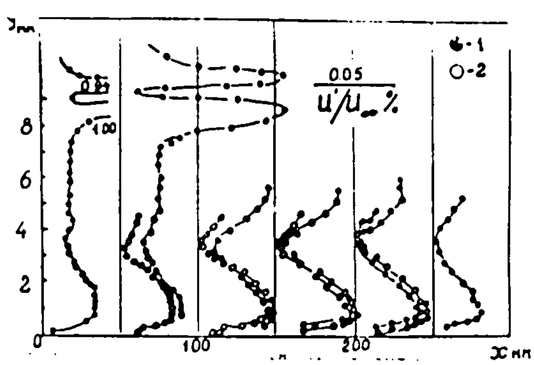

Fig. 9. Amplitude of longitudinal component of velocity pulsations for frequency f=73 Hz (218 $\cdot 10^{-6}$)
1—for perturbation introduced outside the boundary layer.
2—for perturbation introduced inside the boundary layer.

the experimental proof of this effect is controversial, to a considerable extent), then the question of their generation by a concentrated effect on the boundary layer seems trivial at first glance. The classic method of excitation of Tollmin-Schlichting waves is a vibrating band inside the boundary layer. However, the trivial nature is only apparent: the laminar boundary layer is rather conservative, and does not react so easily to external perturbations, which is indicated in the first series of experiments in [28]. Thus, the question of the reaction of the boundary layer to external concentrated effects should be subjected to special study. Only a limited number of studies has been carried out in this area in recent years.

K. Tam [50] theoretically studied the possibility of excitation of unstable waves in a shear layer by external acoustic waves. Calculations showed that the connection between the acoustic and hydrodynamic waves depends substantially on the width of the sound beam, with respect to the thickness of the shear layer, and the narrower it is, the greater the possibilities for excitation of the hydrodynamic waves, and the more intense the excitation process. Carried out in study [51] were calculations of complete Navier-Stokes equations for perturbed movement, when the velocity perturbation is designated as localized in the space outside the boundary layer. According to these calculations, the indicated type of effect leads to the appearance of Tollmin-Schlichting waves in the boundary layer. Carried out in study [52] were experimental studies of this potential mechanism of generation of natural oscillations of the boundary layer. The artificial perturbations were introduced into the flow by a vibrating band, located above the plate outside the boundary layer. Thermal flowmeter measurements of the longitudinal component of the velocity pulsations made it possible to detect the generations of the perturbations in the boundary layer. The results of the study of the characteristics of the detected perturbations, and their comparison with the corresponding characteristics of the Tollmin-Schlichting waves (the latter were excited when a metallic band was located in the boundary layer itself [5], [53]), are presented in Figures 9, 10 and 11.

Depicted in Figure 9 are the profiles of the velocity pulsations of one of the frequencies for perturbations introduced outside the boundary layer, as well as velocity perturbations in the Tollmin-Schlichting wave. If the profile of the studied perturbation in the boundary layer, in the first cross-sections, differs from the profile of the Tollmin-Schlichting wave, then they practically coincide far from the band. In the first cross- /19

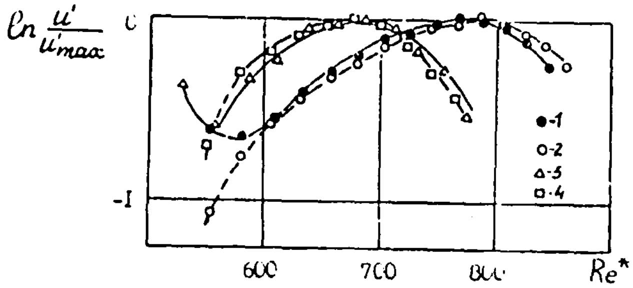

Fig. 10. Curves of increase in perturbations in boundary layer.

1,3—for perturbation introduced outside boundary layer: 1—f=60 Hz ($f=180\cdot10^{-6}$), 3—f=73 Hz ($f=218\cdot10^{-6}$); 2,4—for perturbation introduced inside boundary layer: 2—f=60 Hz, 4—f=73 Hz.

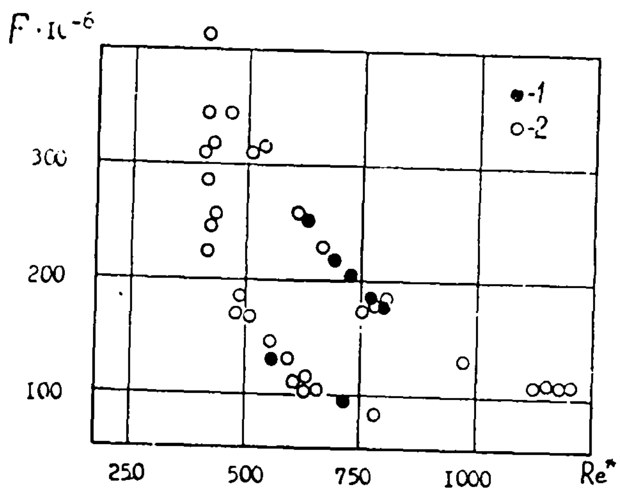

Fig. 11. Neutral points for perturbations developing in the boundary layer.
1—for perturbation introduced outside the boundary layer.
2—results of study [53].

section, the amplitude of the external perturbation u'/u_∞ is marked in percent.

Presented in Figure 10 are the curves of increase, constructed at the perturbation maximum in the boundary layer in the indicated two cases. The behavior of the curves is practically identical at a sufficient distance from the band, while they behave differently close to it.

The phase measurements that were carried out showed that perturbations inside the boundary layer disseminate with a velocity equal to 0.4 of the flow velocity, which corresponds to the velocity of the Tollmin-Schlichting wave.

Discrepancies in the behavior of the perturbation, introduced by the band outside the boundary layer, and the Tollmin-Schlichting wave, reflected in Figures 9 and 10, are a result of the fact that a Tollmin-Schlichting wave does not exist in pure form near the band. Along with this, with the examined type of external effect, there are perturbations present in the boundary layer with wavelengths which are different from the wavelength of the Tollmin-Schlichting wave, which attenuate in proportion to the distance from the band.

Plotted in Figure 11 are the neutral points for several frequencies of the studied perturbations, as compared to the neutral points for small perturbations in the boundary layer of a plate, obtained in study [53]. The agreement of the results is evident.

Thus, analysis of these results, and their comparison with the characteristics of the natural oscillations of the boundary layer, make it possible to conclude that the concentrated effect of external perturbation of small amplitude on the boundary layer leads to the generation of Tollmin-Schlichting waves, in contrast to the distributed effect of an external vortical perturbation.

Thus, one may conclude that, at the present time, the important problem of the excitation of natural oscillations of the boundary layer is beginning to be studied, and appreciable successes are already being achieved in this matter. Some possible paths of transformation of external perturbations of varying nature (acoustic, vortical, vibration) into Tollmin-Schlichting waves, which takes place both in the region of a sharp forward edge and in a developed /20
boundary layer (by means of a concentrated effect), have been de-

tected and studied.

At the same time, the question of the possibility of distributed generation, in the case of a rigid smooth wall, still remains open. Other paths of excitation of Tollmin-Schlichting waves will probably be detected. There is still much work to be done in this direction, both in the area of theory and in an experimental plane.

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