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LAMINAR BOUNDARY LAYER IN CONDITIONS OF "NATURAL" TRANSITION TO TURBULENT FLOW

N.F. Polyakov

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16. Abstract Results of experimental study of regularities of a natural transition of a laminar boundary layer to a turbulent layer at low subsonic air flow velocities are presented, analyzed and compared with theory and model experiments.

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LAMINAR BOUNDARY LAYER IN CONDITIONS OF "NATURAL" TRANSITION TO TURBULENT FLOW

N.F. Polyakov

The development of turbulence in the boundary layer is one of the major key problems of the dynamics of a viscous fluid. Solution of this problem is of great importance both in the general theoretical aspect and in practical applications to different fields of technology. That interest which specialists all over the world display in this question and the continually increasing number of theoretical and experimental studies devoted to problems of the origination and regularities of development of perturbations in the boundary layer and phenomena of transition to the turbulent state are therefore not accidental. The entire complex of studies conducted by different scientists and groups of investigators in this area can be divided into three groups: a. theoretical work; b. model experiments; c. experimental work in conditions of "natural" transition to turbulence. There is no doubt that this division is not exhaustive and that, for individual works, it is difficult to establish the group to which they belong. As a whole however, this classification quite accurately reflects the content of the published works. Without dwelling on group a, we discuss the characteristics and differences between groups b and c. /1

We will understand model studies to be experiments which are characterized by the introduction of artificial perturbations with the capability of changing both the frequency and amplitude of the initial perturbation. Artificial perturbations are most often introduced directly into the boundary layer (by means of a vibrating strip for example). In the "natural" transition to turbulence, studies are made of the regularities of location of the transition region and structure of the perturbations in the boundary layer or, with the ini-

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*Numbers in the margin indicate pagination in the foreign text.

tial characteristic intensities of a given aerodynamic situation, of the nature and spectral composition of the perturbations of the external flow, or by the introduction of given perturbations into the field of the flow incident on the model. The conditions of a model experiment are more easily controlled, and "group b" is therefore most suitable for comparison with the conclusions of theory. This type of study begins with the well known experiments of Schubauer and Skramsted with a vibrating strip, which was taken up in the work of Klebanov and, in the last decade, has been extensively developed in the Institute of Theoretical and Applied Mechanics, Siberian Section, USSR Academy of Sciences, in a series of studies of V.Ya. Levchenko, Yu.S. Kachanov and V.V. Kozlov. Studies under "natural" conditions are exploratory work as a rule, and they are connected with the simultaneous action of a whole series of parameters on the phenomenon studied. The results of such experiments also are quite interesting to theoreticians, since they permit individual regularities to be observed with the construction of new theoretical models. Studies of the "natural" transition to turbulence are more complex, and the number of such studies therefore is evidently limited. /21

This work presents the results of experiments in study of the regularities of the "natural" transition of a laminar boundary layer (LBL) to a turbulent layer at low subsonic air flow velocities. Analysis of these data, their generalization and comparison of the results obtained under various conditions with the conclusions of theory and "model" experiments are conducted. The interpretation of the facts described is based mainly on the results of studies performed in wind tunnel T-324 at the Institute of Theoretical and Applied Mechanics, Siberian Section, USSR Academy of Sciences, published in 1971-1977 by the author or with his participation. A portion of the materials is published for the first time. There is no doubt that his impressions of the opinions reported in the theoretical and experimental works of other investigators have been superimposed on the conclusions and hypotheses expressed below. The work makes no claim to completeness but, on the contrary, it emphasizes the diversity and complexity of the phenomena connected with the origin and development of perturbations of the flow in a laminar boundary layer in conditions of natural transition to turbulence and the need to continue the work in this area. Nevertheless, analysis of the facts presented in the work permit explanation (or confirmation of previously made hypotheses) of the causes of some discrepancies in the results of the experiments of different authors or features of the manifestation of individual regularities.

Thus for example, it is well known that many factors affect the phenomena of transition of a laminar boundary layer to turbulent flow: degree of turbulence of the flow (ε), longitudinal velocity gradients, /25 level and frequency of acoustical pressure, etc. The results of the experiments of Schubauer and Skramsted [1] to determine the relationship between the Reynolds number at the start of the transition (Re_t) and the degree of turbulence of the free flow have become classical and are widely cited in monographs and textbooks. Guided by these data as well as the results of the earlier experiments of Dryden, van Driest and Blumer [2], and based on some theoretical premises, the semiempirical relationship $Re_t=f(\varepsilon)$, which is in quite good agreement with experimental results, was proposed. A number of other studies are known which deal with this question. Subsequent experiments of other investigators show however that, at least in low intensity turbulence, the relationship $Re_t=f(\varepsilon)$ is not unambiguous. The following data are presented in Fig. 1: 1. Schubauer and Skramsted [1]; 2. Wells Jr. [3]; 3. Spengler and Wells Jr. [4]; 4. V.M. Filippov [5]; 5. Barnes [6]; 6. Boltz et al [7]. The open symbols show the results of the author in measurements on a flat plate in different years. The experimental results presented in Fig. 1 both graphically show that function $Re_t(\varepsilon)$ is not universal in the regions of small values of ε and permit formulation of a number of questions:

1. what caused the appearance of "wings" (Re_t=const [illegible]) with $\varepsilon<0.1\%$ from the data of Schubauer and Skramsted?

2. what are the causes of the significant discrepancy of

function $Re_t = f(\varepsilon)$ from the experimental results of [1, 5][1] and of the present work?

3. Why does the "wing" arise with $\varepsilon > 0.08\%$ according to the data of the author?

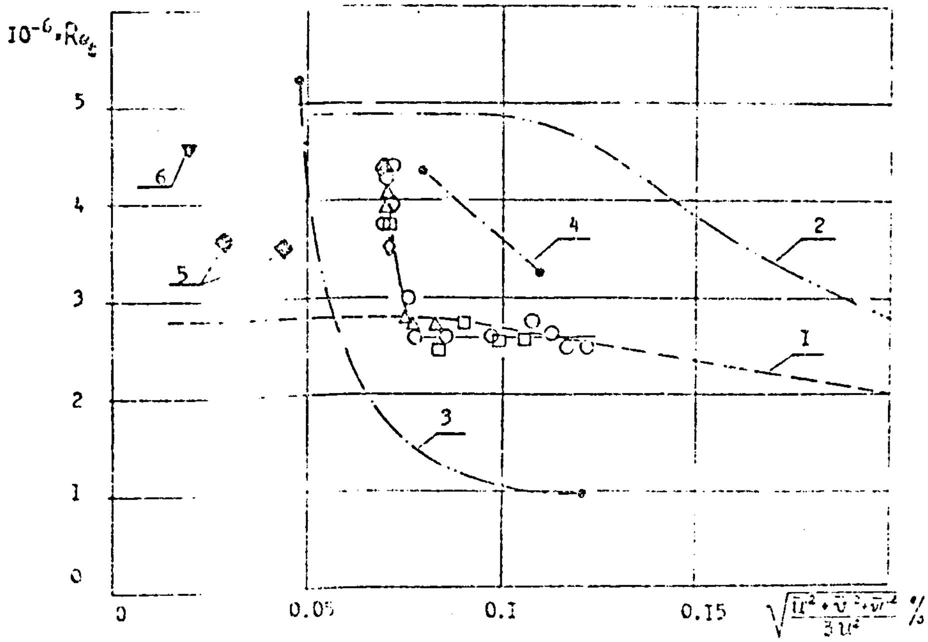

Fig. 1.

A no less complicated situation is observed in the dependence of the transition Reynolds number on frequency and acoustical pressure level according to the data of various authors. Accordingly, the results of the author of the present work and of Spengler and Wells [4] are given in Fig. 2a and 2b. The data in Fig. 2a were obtained in study of the state of the boundary layer on a flat plate with zero

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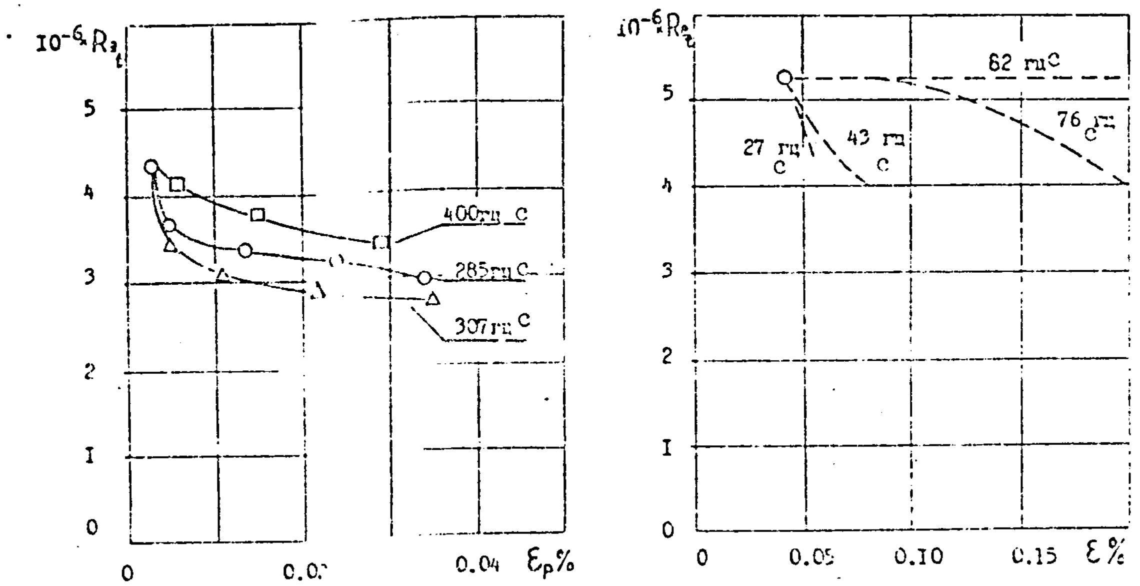
[1] The question of comparison with the remaining results presented in Fig. 1 is not raised here, for the reason that only the experiments of [1, 5] and the present article were performed on a flat plate with known a. nature of pressure distribution along the plate, and b. the conditions of conduct of the experiment.



a a). U = м/сек

b c). U = 12 м/сек; [4]

Fig. 2.

Key: a. U=33 m/s
b. U=12 m/s [4]
c. Hz

pressure gradient and 33 m/s flow velocity. A practically flat longitudinal acoustical field of discrete frequency was imposed on the flow. /28 The acoustical pressure level was reduced to acoustical velocity pulsations (ε_p) by the formulas for a plane wave and dimensionless velocities of the incident flow. The experiments in [4] (Fig. 2b) were performed in study of the state of the boundary layer on the walls of a circular (cross section) working section with U=12 m/s. (In this case, the boundary layer undoubtedly was exposed to a noticeable longitudinal pressure gradient, although the data on the pressure distribution along the working portion are not presented by the authors of [4].) The acoustical pressure level of the longitudinal field was presented here in the form of velocity pulsation intensities, measured with a hot wire anemometer. It follows from Fig. 2a and 2b that function $Re_t(\varepsilon)$ also is not universal. At the same time, a natural question is: why is the monotonic nature of the dependence of Re_t on acoustical frequency f_0, clearly displayed in [4], disturbed in Fig. 2a? The answer to this, just like to the questions raised above, can be found if the experimental facts and the effects of different parameters on the state and spectral composition of the perturbations in the laminar boundary layer are examined in the stages preceding the region of transition to turbulence. One important factor which affects the state of the boundary layer is the value and sign of the longitudinal pressure gradients.

1. Effect of Distributed and Local Longitudinal Pressure Gradients on State of Boundary Layer

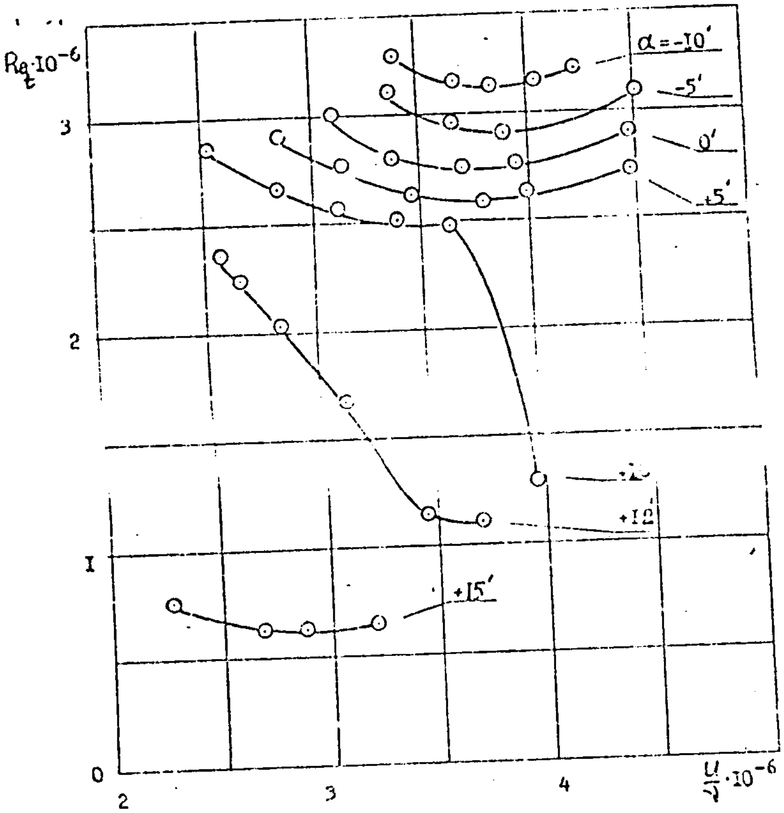


Fig. 3.

As early as the experiments of Schubauer and Skramsted [1], the effect of pressure gradients on the position of the neutral stability curve (NSC) was demonstrated. This question has now been studied theoretically with exhaustive completeness (see [8] for example) within the framework of linear theory for both a two dimensional and a three dimensional laminar boundary layer. The effect of small negative pressure gradients on the Re_t number was investigated experimentally in [5]. An attempt was made in [9, 10] to study the effect of small pressure gradients on the Re_t number, by changing angle of incidence α of a flat plate with an ellipsoidal tip (half axis ratio b:a=1:33) within -10'<α<15'. The results of these measurements (Fig. 3) showed that the Re_t number depends essentially on small changes of the angle of incidence right up to the appearance of crisis phenomena. Analysis of pressure distribution data along the plate showed that small changes of the angle of incidence have almost no effect on the pressure gradient on the primary portion of the plate, but it significantly changes the nature and magnitude of the pressure gradients near the leading edge. These facts permitted the proposal that the main cause of abrupt (right up to critical) changes of the /30

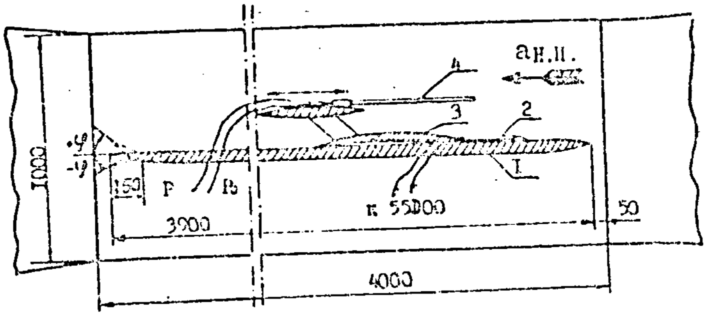


Fig. 4.

Key: a. Incident flow

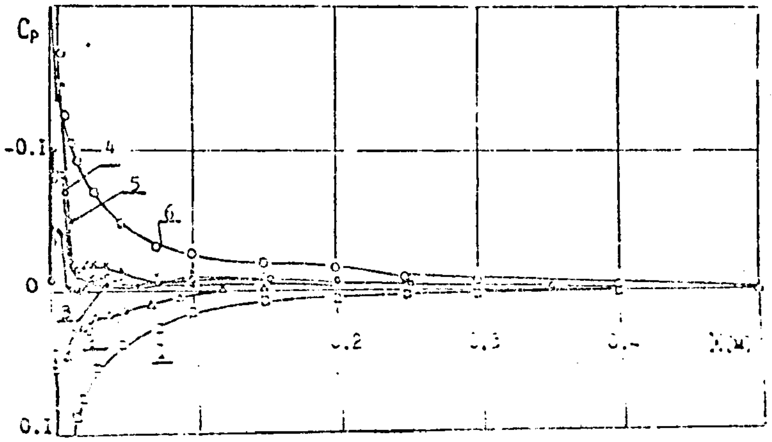


Fig. 5.

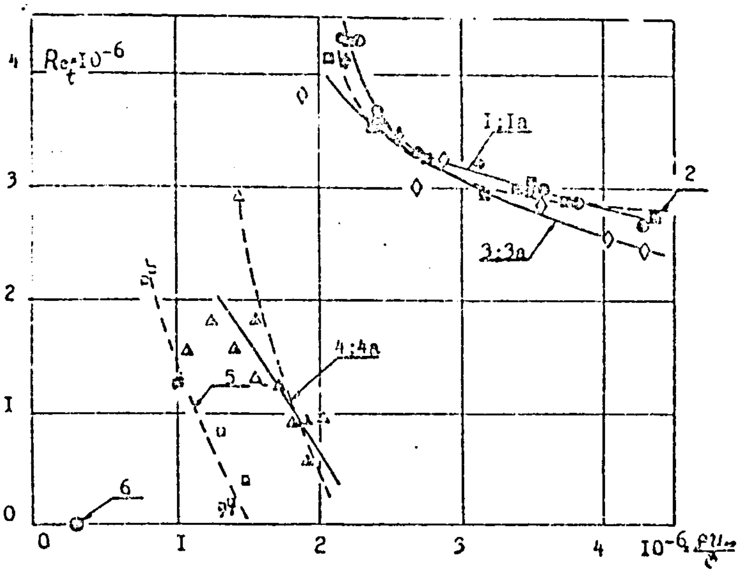


Fig. 6.

Re_t number with small changes of the angle of incidence of the plate are local pressure gradients at the leading edge [9, 10]. To prove this hypothesis and work out a method of control of the nature of the pressure distribution on the initial sections of the plate, a series of experiments was performed [11] on a 3900 mm long plate equipped with a flap which has a 150 mm chord (Fig. 4).[2] A D16T alloy plate with degree of smoothness no worse than ∇9-∇10 and nonplanarity of no more than 0.05 mm/m had an ellipsoidal leading edge with half axis ratio b:a=2 mm:165 mm on the top (working) part of the surface. The lower portion of the initial section was formed of a half ellipse with half axis ratio b:a=1:33 smoothly joined with the entrance of the local curve. The radius of curvature of the leading edge was 0.5 mm. The plate was arranged in the horizontal plane and occupied the entire width of the working section (1.0 m). A small change of angle of adjustment ϕ of the flap permitted action on the nature of

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[2] To establish a "soft" access of the flow to the plate and create a favorable pressure distribution on the leading edge, installation of a series of bars across the flow in the area of the trailing edge of the plate was used in [5].

pressure distribution at the leading edge without affecting the pressure gradient on the main part of the plate. The nature of the pressure distribution on the leading edge of the plate with different angles of adjustment ϕ of the flap is shown in Fig. 5. Measurement of the Reynolds number of the start of the transition (Re_t) as a function of flow velocity (or, which is the same thing, of unit Reynolds number U/ν m^{-1}), with varied pressure distribution on the leading edge of the plate, is presented in Fig. 6. The numbering of the curves in Fig. 6 corresponds to the Fig. 5 data. The "a" symbols of some Fig. 6 numbers mean that the measurements were conducted twice with resetting of angle ϕ of the flap. In these cases, indices of the same geometry on a curve are distinguished by shading. The results presented in Fig. 5 and 6 indicate that the nature of the pressure distribution on the leading edge of the plate, especially when sections with positive pressure gradients are present, sharply affects the position of the region of transition to turbulence. The appearance of even small rarefaction peaks (curve 3 for example) leads to instability of the beginning of the transition region and to scattering of the experimental values of Re_t. We note that the entire series of measurements presented in Fig. 5 and 6 was performed with a small positive velocity gradient above the main section of the plate equal to $\frac{1}{U}\cdot\frac{dU}{dX}=0.0035$ m^{-1}, since the angle of incidence of the plate (along the working part of the surface) was 0 in this case. /31

With the abovementioned taken into account, it becomes clear why, in reference to Fig. 1 in the introduction, the stipulation was made of comparability of the data of only three works ([1, 5] and the present work). The nature of the pressure distribution on the initial sections of the plates for these works, which correspond to function $Re_t(\varepsilon)$ in Fig. 1, is presented in Fig. 7 (1. data of author; 2. from [1]; 3. from [5]).

The attention of the reader should be drawn to still another circumstance. High values of the numbers $Re_t \leq 4.5\cdot 10^6$, obtained by the author and in [5], are not only associated with the quite low level of perturbation of the flow with appropriate establishment of

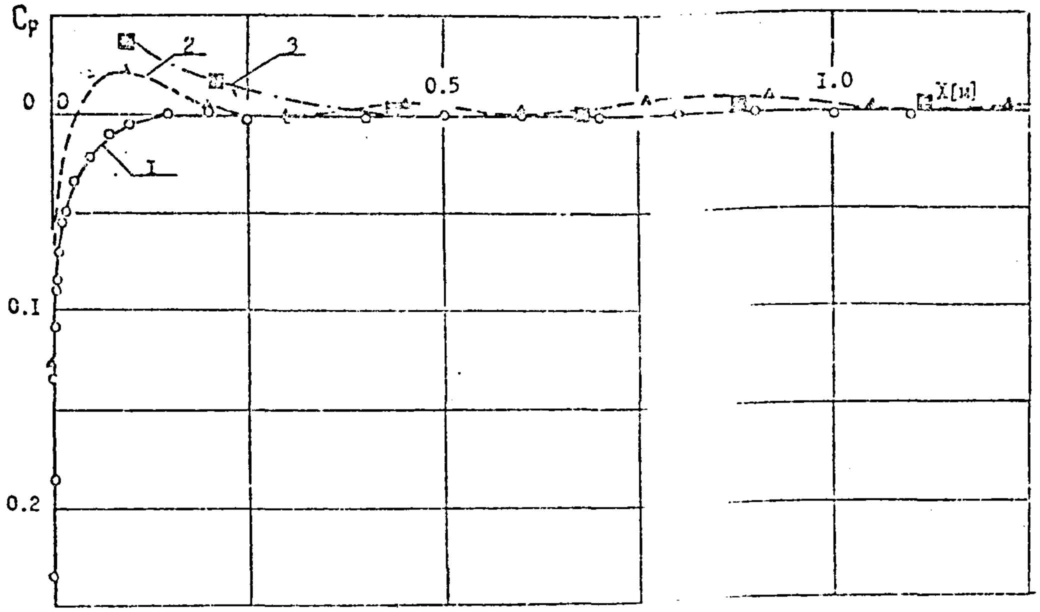


Fig. 7.

the nature of the pressure distribution along the plate. With a larger size working section (larger span dimension of the plate), the Re_t number can be higher. The fact is that, in the interaction of the boundary layers at the points of joining of the plate with the vertical walls of the working section, a turbulent layer originates, which forms turbulent wedges downstream from the leading edge with aperture angle 11°-12°. The limiting extent of the laminar layer, even with low velocities and plate span b=1 m, therefore does not exceed a value of approximately 2.2 m along the plate axis. This fact was investigated by V.N. Filippov and confirmed by measurements of the author. We also note that, for a plate with b=1 m for example, an increase of flow velocity (in the range $U<30-33$ m/s) can only result in an apparent increase of the Re_t numbers, since the positions of the turbulent wedges remains fixed in a specific range of velocities. The experiments of Filippov [5] and of the author of the present lines show that an increase in flow velocity beyond the limits of this range leads to a decrease of the Re_t numbers. The question of the effect of velocity will be discussed below in Section 6.

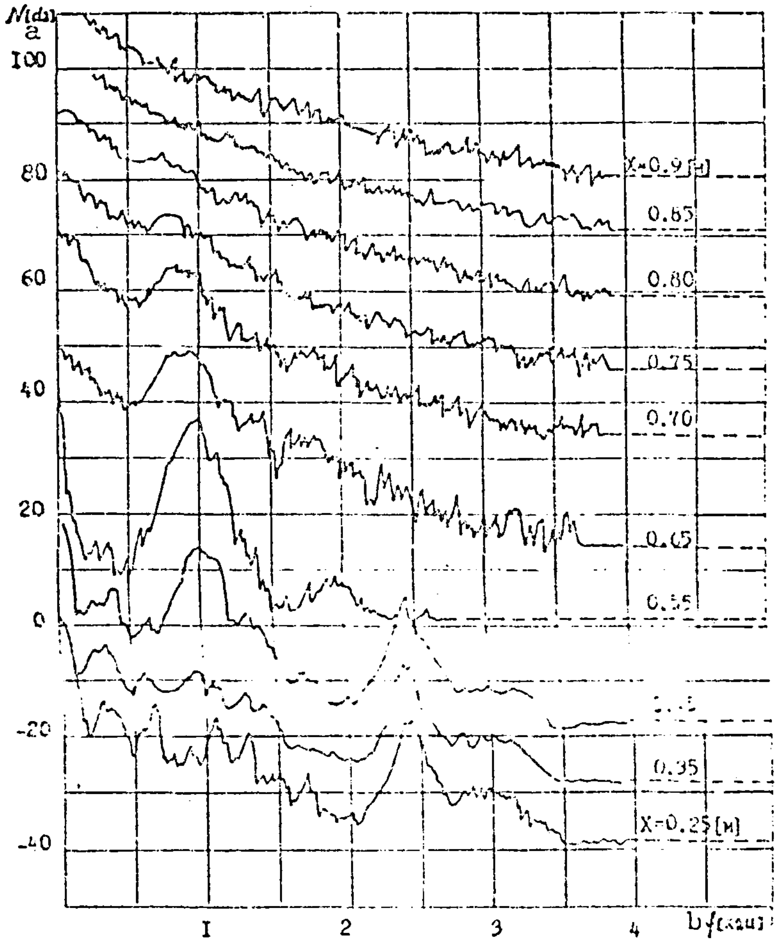
2. Frequency Spectra of Perturbations in Laminar Boundary Layer

Studies of the frequency spectra of the U' component of the velocity /4 pulsations in the boundary layer at different stages of its development were performed with near zero pressure gradients in the main sections of the plate [9, 12]. A typical series of spectrograms are presented in Fig. 8, with degree of turbulence of the incident flow $U'/U \approx 0.04\%$ and external flow velocity $U=51.5$ m/s ($U/\nu=3.18\cdot10^6$ m^{-1}). The hot wire anemometer sensor was moved a fixed distance from the surface of plate of approximately $y/\delta^* \approx 1$. For convenience in examination, each subsequent spectrogram was displaced +10 dB relative to the preceding one. The band of clipped frequencies is constant and is $\Delta f=6$ Hz. A series of spectrograms is presented in Fig. 9, with artificially increased degree of turbulence $U'/U=0.41\%$ ($U=40.5$ m/s, $U/\nu=2.45\cdot10^6$ m^{-1}). Each subsequent spectrogram also is displaced +10 dB relative to the preceding one with increase in distance from the leading edge of 100 mm. Spectrogram 1 corresponds to $X=0.2$ m. The unnumbered spectrogram in Fig. 9 shows the noise level of the equipment at $U=0$. Analysis of the spectrograms in Fig. 8 and 9 (and those similar to them which correspond to other flow parameters) permits attention to be drawn to a number of facts.

1. In the laminar boundary layer with small ($\varepsilon_u \approx 0.04\%$) and medium ($\varepsilon_u \approx 0.4\%$) levels of perturbation, there practically always is a package of frequencies which correspond to the instability region, with a predominant amplitude. With increase in Reynolds number, the amplitude of the central frequency of this package ("fundamental tone") increases.

2. In the power spectra, besides the "fundamental tone," there also are packages of higher frequencies, which evidently reflect nonlinear effects, as well as lower frequencies which exist in a continuous spectrum as a rule.

3. An increase in amplitude of the "fundamental tone" is observed only within the theoretical instability region (Fig. 10). The



$u/\nu = 3{,}18\cdot10^6 м^{-1}$; ($u=51{,}5$ м/с); $\varepsilon = 0{,}04\%$.

Fig. 8.

Key: a. N, dB
b. f, kHz
c. u=51.5 m/s

frequency of the "fundamental tone" decreases with approach to the second branch of the neutral curve. Destruction of the "regular" vibrations of the "fundamental tone" with formation of turbulent spots occurs in the inner zones of the instability region as a rule, but always within the latter.

4. With approach to the transition region, together with an in-

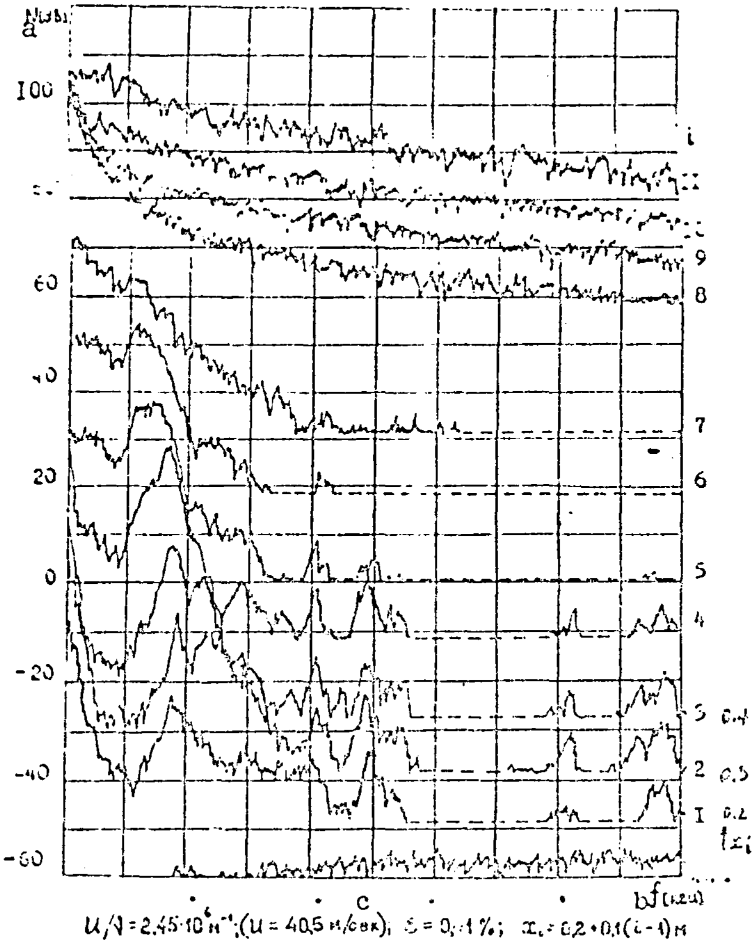


Fig. 9.

Key: a. N, dB
b. f, kHz
c. u=40.5 m/s

crease in amplitude of the "fundamental tone," intensive increase in amplitude of the low frequency vibrations in the continuous spectrum is observed. The physical meaning of this interaction became clear from model experiments [13] on the interaction of wave packages of two close frequencies, the development of which led to the formation and intensive development of the difference frequency vibrations. In conditions of "natural" transition, this process is of a random nature. The difference frequency in the power spectra therefore is not discrete, and the effect of appearance of the difference frequencies is manifested by an increase of the low frequency components in the continuous spectrum.

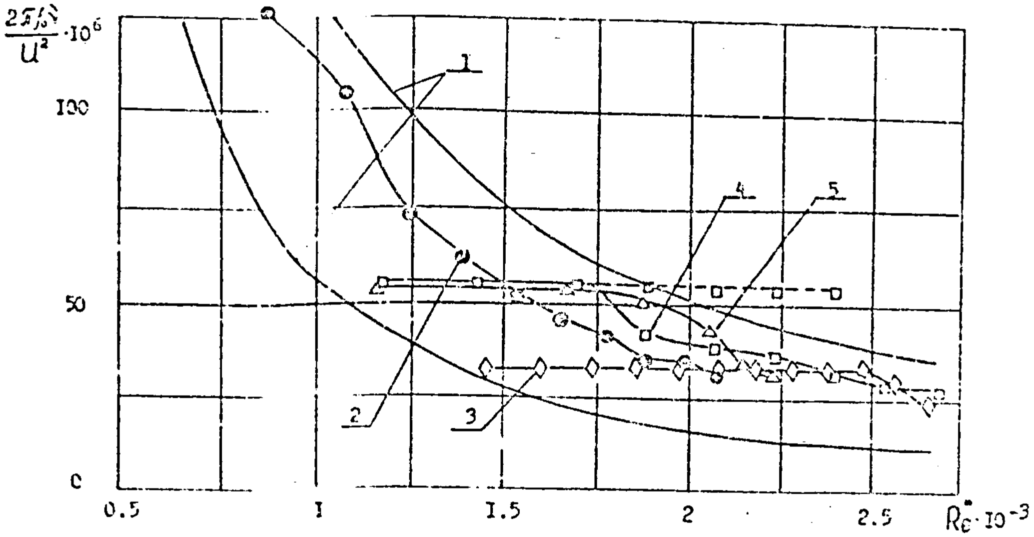


Fig. 10. 1. Neutral stability curve; 2. U=21.9 m/s, ε_u=0.41%; 3. U=52 m/s, ε_u=0.033%; 4. U=41.2 m/s, ε_u=0.026%; 5. U=40.5 m/s, ε_u=0.41%.

We consider the circumstance that, with the appearance of turbulent spots, an appreciable increase of the higher (compared with the "fundamental tone") frequencies begins in the continuous spectrum, the increase of which with increase in the alternation factor leads to smoothing of the power spectrum and its approach to the form characteristic of developed turbulent flow (see spectra with X≥0.65 m in Fig. 8 and No. 7 and higher ones in Fig. 9).

We also note that an increase in the degree of turbulence of the external flow to 0.41%, accomplished by installation of a d=0.3 mm wire grid with 5 mmx5 mm mesh at the start of the working section did not change the fundamental structure of the perturbations in the boundary layer [9], although it resulted in earlier transition to turbulence (Re_t=1.6·10^6 with ε_u=0.41% and Re_t=2.6·10^6 with ε_u=0.05%).

This evidently is associated with the situation that a change in degree of turbulence of the external flow, as the measurements showed, led to broadening of the perturbation spectrum in the direction of higher frequencies right up to 5 kHz, practically without affecting the low frequency pulsations observed with a low degree of turbulence.

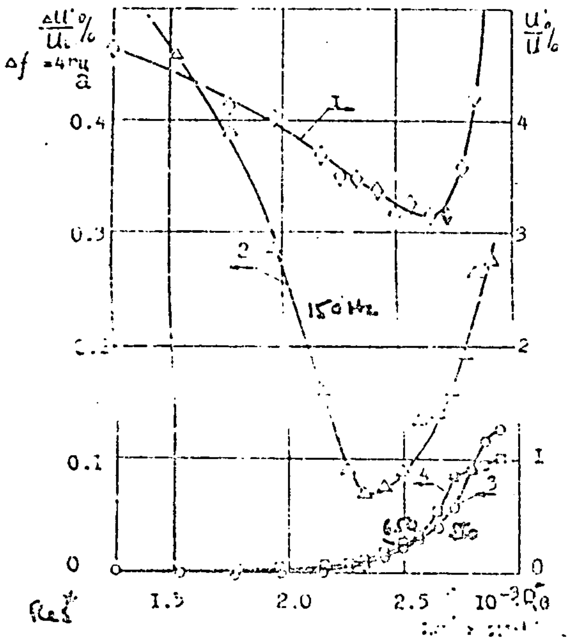


Fig. 11. U=43.5 m/s; $U/\nu=2.63\cdot10^6$ m^{-1}; 1. $(u'/u_1)\Delta f$=10 Hz-5 kHz; 2. f=150 Hz, $F=8.2\cdot10^{-6}$; 3. f=550·Hz, $F=30\cdot10^{-6}$; 4. f=650 Hz, $F=35.5\cdot10^{-6}$.

Key: a. Δf=4 Hz

Analysis of the spectrograms of velocity pulsations in the boundary layer combined with the spectrograms of perturbations of the external flow (velocity pulsation and pressure pulsation component), as well as of the vibration spectrograms of the plate under study, shows that the package of the discrete frequencies of the "fundamental tone" corresponds in the majority of cases to the clearly distinguished packages of the same frequencies in the external perturbation spectra. Although discrete frequency packages in the external perturbation spectrum are observed in other cases, they are less clearly distinguished. These facts permit the proposal that the origination and development of discrete packages of hydrodynamic waves ("fundamental tone") which correspond to the instability regions occur in /39
the laminar boundary layer in the cases under study due to the discrete components of the same frequencies in the external perturbation spectra [14]. However, comparison of the external perturbation energies with the pulsation intensities observed in the boundary layer and the absence of measurements which permits tracing of the mechan-

ism of penetration of external perturbations into the boundary layer do not permit these facts to be considered absolutely proven at this stage. Some doubt is introduced into this question by the fact that measurements of the external perturbations were made in the flow above the working part of the plate. The completely natural question therefore arises: which of the measured values is primary and which is derivative? Only supplementary experiments can give an answer to this question.

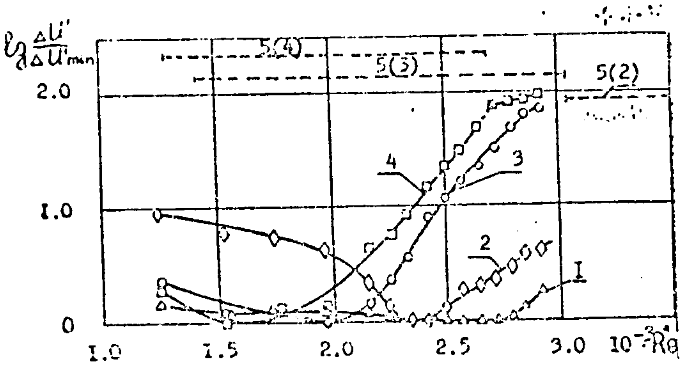


Fig. 12. $U=43.5$ m/s; $U/\nu=2.65\cdot10^6$ m^{-1}; $y/\delta=0.24$; $\bar{U}=0.4=$const; 1. U' in 10 Hz-5kHz frequency band; 2. $\Delta U'$; f=150 Hz; 3. $\Delta U'$; f=550 Hz; 4. $\Delta U'$; f=650 Hz; 5(3), 5(4), 5(2) is the instability region.

It was shown in [15] that the conversion of external perturbations at the leading edge of the plate is one possible mechanism of excitation of Tollmin-Schlichting waves in the boundary layer. Manifestations of this mechanism under natural conditions will be presented below in the appropriate section, but we now discuss how perturbations of some characteristic frequencies develop in a laminar boundary layer. It followed from the velocity pulsation spectrograms measured at $U=43.5$ m/s ($U/\nu=2.62\cdot10^6$ m^{-1}) in the boundary layer near the leading edge before the appearance of the turbulent spots that the perturbation packages with central frequencies f=150 Hz, 550 Hz and 650 Hz corresponding to frequency parameters $F=\frac{\omega\nu}{U^2}=8.2\cdot10^{-6}$, $30\cdot10^{-6}$ and $35.5\cdot10^{-6}$ merit the greatest attention. For these frequencies, the intensity distribution of velocity pulsations in the $\Delta f=4$ Hz frequency band was measured as a function of the Re' number (see curves 2, 3 and 4 in Fig. 11) with $U/U_\delta=$const, as well as the integral intensity of the velocity pulsations in the frequency band from 10 Hz to 5 kHz (curve 1 in Fig. 11). The shaded symbols at $Re''\approx2.7\cdot10^3$ note the point of appearance of turbulent spots. The fact that, before the transition to turbulence, the integral pulsation intensity exceeds the pulsation intensity of the discrete frequency packages by more than an order of magnitude attracts attention. It is evident however that precisely the discrete frequencies play a decisive role in the transition phenomenon, since the intensive increase in amplitude of these frequencies begins long before the appearance of turbulent formations. This follows more graphically from Fig. 12, in which the Fig. 11 data are presented (with the same notations) in the semilogarithmic scale, where the amplitudes of the velocity pulsations /41 at each point are relative to their minimum values. It is clearly evident that oscillations of quite small absolute value from central frequency f_0=650 Hz (curves 4; $F=35.5\cdot10^{-6}$) play the main part in the transition phenomena. Precisely this wave process, the amplitude of which increases by two orders of magnitude, begins to decay with the appearance of the turbulent spots. The position of the theoretical instability region for the discrete frequencies selected in the experiment is designated by the dashed lines in the upper part of the graph (correspondence of the range of Re" numbers of the instability region for a given rise curve is indicated by the number in parentheses). It is evident that the development of vibrations with frequency f=650 Hz (just as with frequency 550 Hz) occurs entirely within the limits of the instability region. It is noteworthy that the rise of the 150 Hz pulsations begins long before approach to the first branch of the neutral stability curve (see curve 2 and dashed line 5(2) in Fig. 12).

The facts presented permit it to be stated that, despite the complexity of the perturbation structure, the laminar boundary layer in conditions of a "natural" transition to turbulence, at least at low and medium levels of external flow perturbations, basically obeys the regularities and conclusions of stability theory. We particularly emphasize that, under the conditions described, the appearance of turbulent spots is associated with destruction of the frequency package which corresponds to the zone of the theoretical instability region, and the transition to turbulence consequently occurs as the result of the development of Tollmin-Schlichting waves. In all the cases discussed above, the average velocity profile right up to the appearance of turbulent spots corresponded to a Blasius profile.

3. Structure of Perturbations in Laminar Boundary Layer with Increase in Turbulence of External Flow

Schubauer and Skramsted [1] noted that observation of regular oscillations (Tollmin-Schlichting waves) in the laminar boundary layer during the natural transition became possible only after the turbulence of the incident flow was significantly reduced. It is therefore natural to raise the following questions: a. what are the characteristics of the spectral composition of the perturbations in the boundary layer upon increase of turbulence of the incident flow? b. are the regularities of the transition to turbulence characteristic of a low level of external perturbations observed in this case?

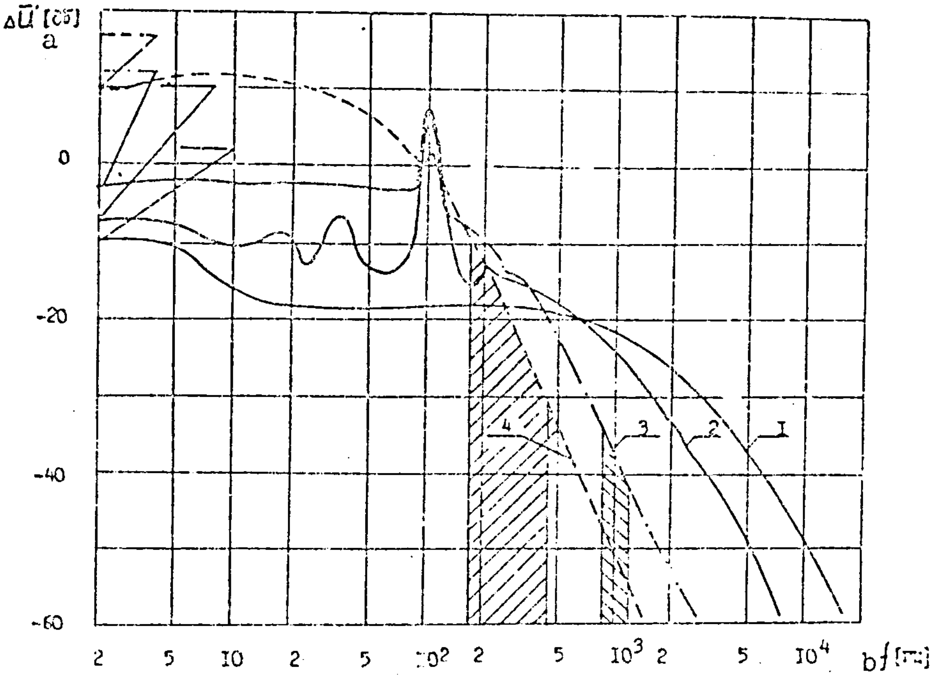


Fig. 13. $\bar{U}=0.45=\text{const}$; $\varepsilon_\infty=0.7\%$; $U=21.0$ m/s; 1. $x=-0.05$ m; 2. $x=0.015$ m; 3. $x=0.075$ m; 4. $x=0.4$ m.

Key: a. $\Delta\bar{U}'$, dB
b. f, Hz

We obtain the answers to these questions by examination of the results of experiments to investigate the frequency structure of the perturbations in the laminar boundary layer of a flat plate with degree of turbulence of the incident flow $\varepsilon_u \approx 0.7\%$. The spectral composition of the U' component of the velocity pulsations in the boundary layer is presented in Fig. 13, with flow velocity U=21 m/s at the following distances from the leading edge: curve 2. X=0.015 m, Re"=250; curve 3. X=0.075 m, Re"=550; 4. X=0.4 m, Re"=1280. These data were obtained with $\bar{U}=U_i/U\delta=0.45$. This corresponds to the maximum intensity throughout the layer. The spectral composition of the incident flow perturbations with X=-0.05 m is shown by curve 1. The basic regularities of the perturbation spectra with increased turbulence is that, with increase in Reynolds number: a. the integral level of the perturbations increases (see horizontal lines on insets in the left part of the graph); b. the spectra become more and more filled in the low frequency region with simultaneous "filtration" of the high frequencies; c. the development of perturbations occurs in a smooth spectrum without segregation of discrete frequencies.[3] In order not to clutter up the picture, the perturbation spectra for X=0.125 m and X=0.25 m measured in the experiments are not presented in Fig. 13. These curves are located between lines 3 and 4, in complete agreement with the regularities reported above. Pulsation spectra with number Re"=1280 (the Reynolds number of the start of the transition is $0.78\cdot10^6$ or $Re''_n=1520$) in the boundary layer with $\bar{U}=0.45$ (curve 1) and at its boundary with $\bar{U}=1$ (curve 2). These data confirm the conclusion that, with increase in turbulence, the boundary layer operates as a high frequency "filter" and low frequency "amplifier."

The cross hatched columns in Fig. 13, 14 designate the theoretical unstable frequency region for the corresponding Re" numbers. It is evident here that, with increase in Re number, the lower frequency oscillations develop actively, but the frequency amplitudes, which should increase according to linear stability theory, die out.

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[3] The reasons for development and role of a package of discrete frequencies with $f\approx100$ Hz will be discussed below in Section 5 of the present work.

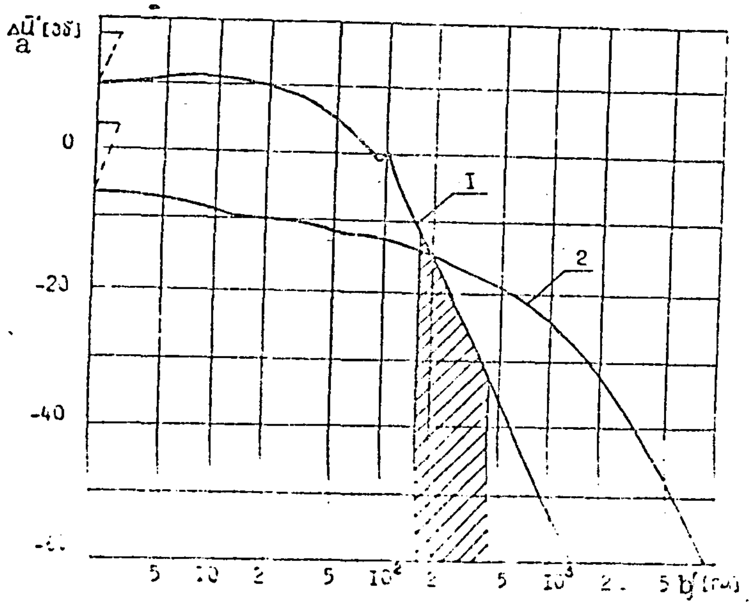

Fig. 14. ε=0.7%; U=21 m/s; X=0.4 m; Re"=1280; Re"$_n$=1520; 1. Ū=0.45; 2. Ū=1.

Key: a. ΔŪ', dB
b. f, Hz

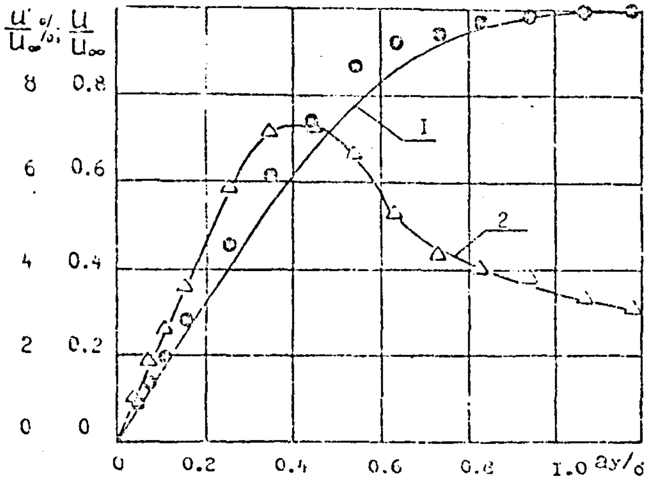

Fig. 15.

Key: a. y/b

The region of transition to turbulent conditions is characterized by broadening of the spectrum in the higher frequency region, with gradual adjustment of the average velocity profile to the form characteristic of a developed turbulent boundary layer. /1

With increase in turbulence of the incident flow, the average velocity profile is more filled than the Blasius profile (solid line 1 in Fig. 15; the points, experiment). This corresponds to the data of [16, etc.]. Since the average velocity profile occupies an intermediate position between the Blasius profile and the profile of a developed turbulent layer with increase in degree of turbulence, such a boundary layer was called pseudolaminar in the work of Ye.P. Dyban and E.Ya. Epik [16, etc.]. The nature of the intensity distribution of the velocity pulsations throughout the boundary layer is presented in Fig. 15 (curve 2). The results of these experiments confirm the hypothesis of Rogler and Reshetko that, "with increase in the intensity of external flow perturbations, the development of perturbations in a laminar boundary layer can occur with an augmented transition to nonlinear interaction (and to turbulence) by bypassing the stage of formation and subsequent amplification of Tollmin-Schlichting waves" [17]. We thus see that, in conditions of an increased degree of turbulence of the external flow, the transition to turbulent flow in the laminar boundary layer, in distinction from the conditions with reduced turbulence, occurs according to its own principles, bypassing the stage of development of Tollmin-Schlichting waves. It can be stated in this respect that, depending on the degree of turbulence of the external flow, there are at least two different types of mechanism of the development of perturbations in the boundary layer in the "natural" transition to turbulence.

4. Effect of Longitudinal Acoustical Field of Discrete Frequency on Boundary Layer Structure and State

The question of the effect of sound on the state and structure of the boundary layer merits special attention for two reasons:

1. the boundary layer in full scale conditions of flight vehicles is subjected to the action of acoustical fields of different levels and spectral composition as a rule;

2. wind tunnels, even with a very low level of perturbation of the flow, have their characteristic acoustical fields of a given level of acoustical pressure with the frequency spectrum features /47

characteristic of a given installation.

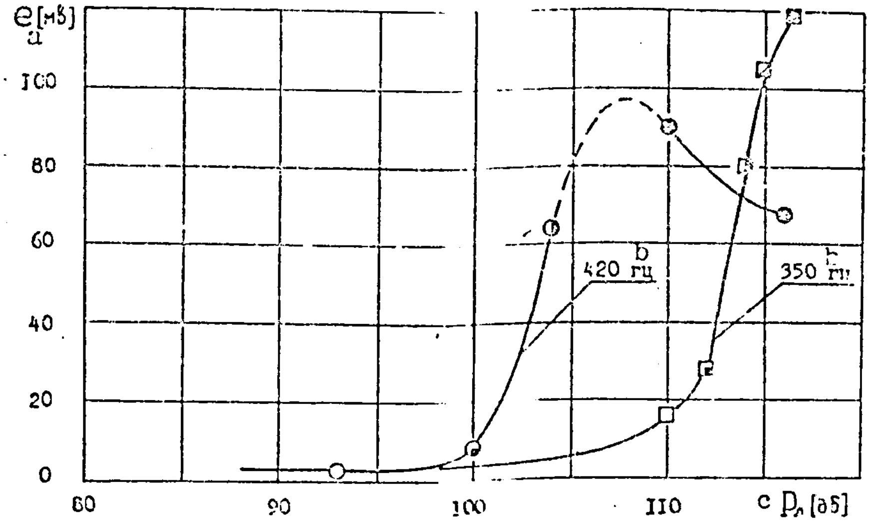

Fig. 16. U=30 m/s; $Re_x=2.03\cdot10^6$; $Re_t\geqslant2.8\cdot10^6$.

Key: a. e, mV
b. 420, 350 Hz
c. Pℓ, dB

The significant difference of function Re_t (ε_p, f_0) from the data of various authors (see Fig. 2a and 2b) was pointed out in the introduction. Different aspects of the effect of a flat longitudinal acoustical field on the state of a laminar boundary layer have been discussed by many authors and reported in particular in [18, 19, 21]. Without dwelling on details of the conduct of these studies, we only note the basic conclusions by way of reporting. The studies showed that, with constant Re number <Re_t and a constant acoustical pressure level, the laminar boundary layer is sensitive to discrete sound frequencies only in a specific "active" frequency band which covers part of the theoretical instability region and is located mainly beyond the limits of branch II of the neutral curve [18, 20]. A sharply defined role of only individual discrete sound frequencies, as follows from [4, 21], has not been revealed. By changing the acoustical pressure level of any discrete "active" frequency, varied boundary layer states (from the excited laminar to the developed turbulent) could

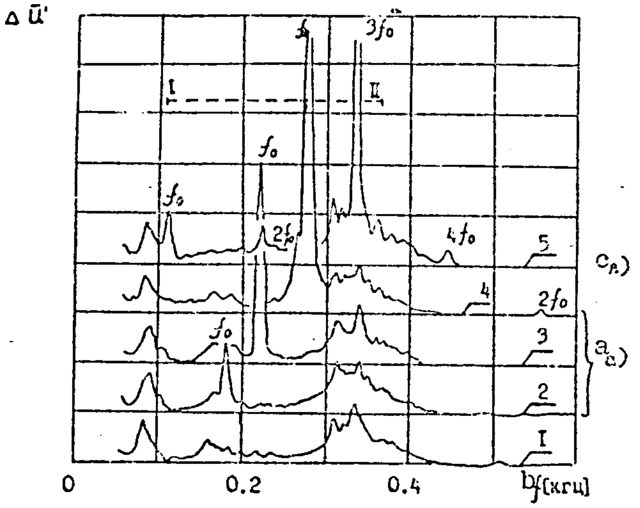

Fig. 17.

Key: b. f, kHz

easily be induced (with $Re<Re_t$). Thus, for example, for $Re=2.03\cdot10^6$ (U=30 m/s, "natural" transition with $Re_t \geqslant 2.8\cdot10^6$) the reactions of the boundary layer (e, mV, is the root mean square value of the voltage pulsations at the hot wire anemometer output) as a function of the acoustical pressure level for acoustical frequencies f_0=350 Hz and 420 Hz, is presented in Fig. 16. The

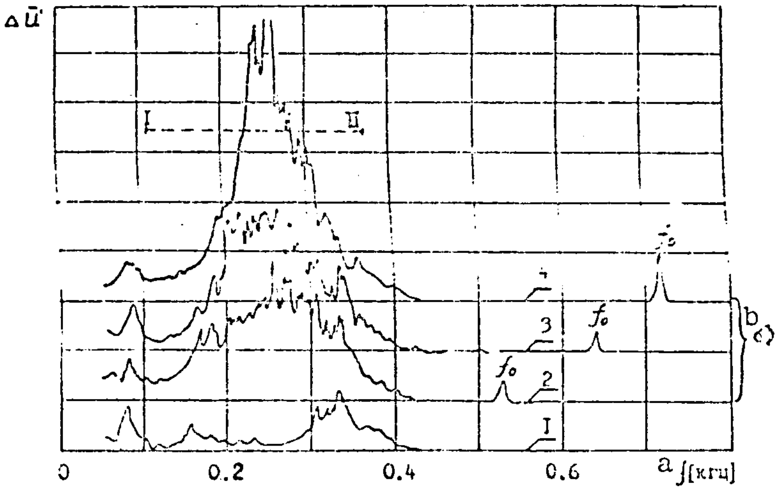

Fig. 18.

Key: a. f, kHz

varied degrees of shading of the symbols correspond to the value of the alternation factor of the observations of the signal on the screen of an electron beam oscillograph. Analysis of the power spectrum (Fig. 17 and 18) of the velocity fluctuations in the boundary layer

($Re<Re_t$) upon exposure to various discrete sound frequencies f_0 from the "active" band showed that, depending on the position of frequency f_0 relative to the theoretical instability region (dashed line I-II), four types of interaction can be distinguished: a. "direct resonance" (curves 2-4 in Fig. 17); b. "induced resonance" (curves 2 and 4 in Fig. 18); c. "direct resonance" from one harmonic of a given sound frequency (curve 5 in Fig. 17), as well as d. "direct resonance" with a low sound amplitude changing to "induced resonance" with increase in acoustical pressure level [18, 20]. The last type of interaction was observed when sound frequency f_0 coincided with branch II of the neutral stability curve. We note that curves 1 in Fig. 17 and 18 represent the spectrum of perturbations in the boundary layer in the absence of acoustical exposure. The logarithmic amplitude scale is the same for all measurements in Fig. 17 and 18. Each subsequent spectrogram is displaced by one division relative to the preceding. The results of the experiments presented in Fig. 16-18 permit the hypothesis to be stated [6 et al] that the Re_t=const "wing" with $\varepsilon<0.1\%$ in the tests of Schubauer and Skramsted is associated with a high acoustical pressure level (105-107 dB) in the wind tunnel of the National Bureau of Standards. The power spectra of the pertubations (predominantly acoustical) of this installation contained discrete frequencies $f=60$ and 95 Hz, the harmonics of which correspond to the "active" frequency band. Therefore, with $\varepsilon<0.1\%$, a change of the turbulent mode affected the Re_t number but, with $\varepsilon<0.1\%$, the leading role in the development of perturbations in the boundary layer and in the transition to turbulence was that of the acoustical mode, the intensity and power spectrum of which remained constant. This is the answer to question No. 1 in the introduction. /4

Study of the mutual time and space correlations between the pressure pulsations in the flow and the velocity fluctuations in the boundary layer due to type a interactions ("direct resonance") showed that, upon exposure to sound, hydrodynamic waves of the same frequency f_0 originate and actively develop in the laminar boundary layer. The region of existence of these waves is included between the axial line of the instability zone and branch II of the neutral stability curve

(NSC). The wavelengths of the sound induced hydrodynamic waves in this type of interaction, as well as their phase velocities correspond to the predictions of linear stability theory [18, 19].

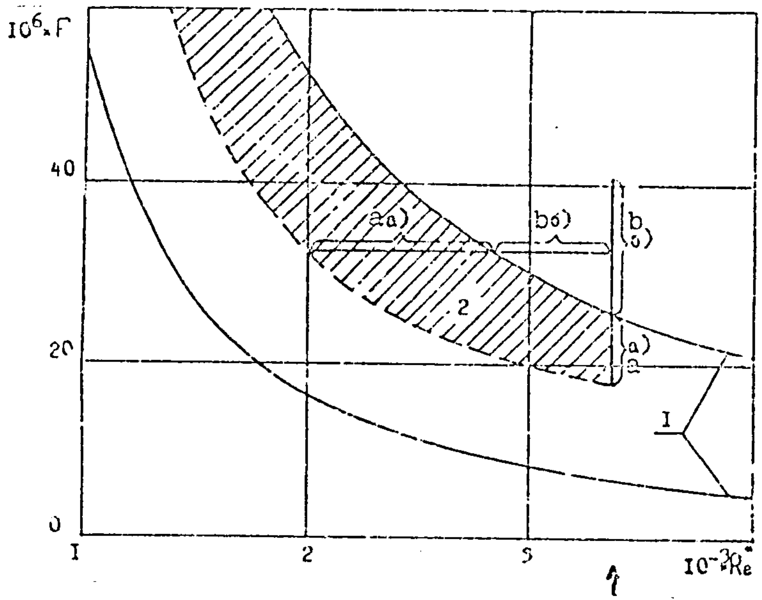

Fig. 19.

Subsequent experiments and observations of the boundary layer structure exposed to an acoustical field showed that the abovementioned types of interaction are essentially the same process, where the type of interaction depends basically on the position of the observation point in frequency-Reynolds number coordinates. We turn to Fig. 19, in which the following are represented: 1. branches 1 and 2 of the theoretical neutral stability curve; 2. region (cross hatched) of existence of intensely developing hydrodynamic waves excited by sound of frequency f_0 according to [18]. The vertical line at $Re^*=3370$ corresponds to the "active" band of acoustical frequencies for a given Re number (see Fig. 1 from [18]). Segment "a" on this line corresponds to the "direct resonance" frequencies, and segment "b" corresponds to the "induced resonance." It is clear that the type "c" /51
interaction is a particular case of "direct resonance," and that it

is manifested with the imposed sound of the higher harmonics present in the spectrum. The type "d" interaction is observed upon coincidence of the sound frequency with the second branch of the neutral stability curve (at the junction of the type "a" and "b" interactions), and it is associated with the level of the acoustical energy supplied. The basic types of interaction should thus be considered types "a" and "b." "Direct resonance" is observed in extensive region 2 (Fig. 19). Experiments show that if, with a fixed acoustical pressure level and constant sound frequency f_0, which corresponds for example to dimensionless frequency $F=32.5 \cdot 10^{-6}$ (see the horizontal line in Fig. 19), to study the frequency structure of the perturbations in the boundary level with increasing Re numbers, a type "a" interaction is observed initially and then the "induced resonance" (type "b"). In other words, hydrodynamic oscillations with sound frequency f_0 originate and actively develop as a result of the sound in region 2 but, upon reaching branch 2 of the neutral stability curve, velocity fluctuations with frequency f_0 transmit their energy to lower frequency wave packets which correspond to the inner zones of the instability region. A similar "fundamental tone" behavior is observed in the natural transition (see [9, 12], as well as Fig. 10 of the present work).

Based on the abovementioned, we attempt to answer the question as to the causes of the disagreement of the results of the experiments presented in Fig. 2a and 2b. The amplitude-frequency curve of the plate vibrations due to sound of an equal level is presented in Fig. 20. Comparison of these data with function $Re_t\ (\varepsilon_p,\ f_0)$ for three randomly selected sound frequencies of the "active" band (Fig. 2a) shows that disturbance of the monotonic nature of function $Re_t\ (f_0)$ with ε_p=const correlates well with the amplitude of the induced vibrations of the plate. There is quite good agreement between the data in Fig. 20 and the certain "hollowness" of the boundary layer reaction at the frequency of the acoustical field (see Fig. 1 in [17]). These facts permit it to be proposed that the acute resonance sensitivity of the boundary layer to only individual frequencies is connected in [4] with the natural frequencies of the experimental installation. A similar conclusion was drawn in [23].

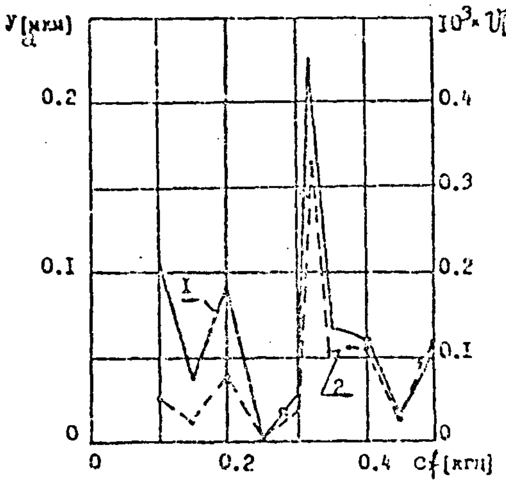

Fig. 20.

Key: a. y, μm
b. 10^3xU, m/s
c. f, kHz

The types of interaction discussed above are related to both the frequency structure of the perturbations in the boundary layer and the nature of the disruption of the laminar conditions in the transition to turbulence. A series of curves of increase of intensity of velocity pulsations in the boundary layer as a function of the Re" number, sound frequency and acoustical pressure level is presented in Fig. 21 for flow velocity U=33 m/s ($U/\nu=2.03\cdot10^6$ m^{-1}). The shaded symbols on the

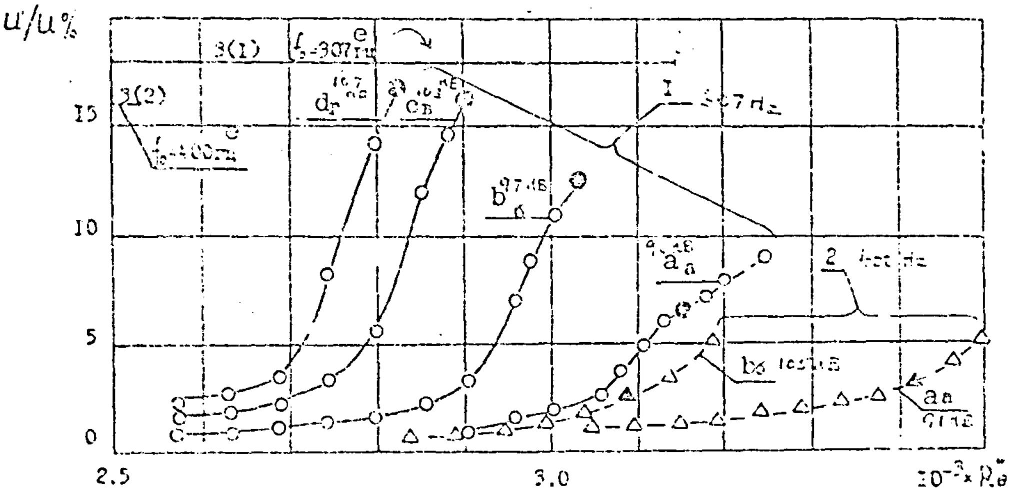

Fig. 21. U=33 m/s; $U/\nu=2.03\cdot10^6$ m^{-1}.

Key: e. f=307 (400) Hz

curve denote Reynolds number Re_t" of the start of the transition to turbulence. Curves 1 correspond to sound frequency f_0=307 Hz with acoustical pressure level in the 1/3 octave band: a. P=90 dB; b. P=97 dB; c. P=103 dB; d. P=107 dB. Curves 2, f_0=400 Hz: a. P=91 dB; b. 105 dB. It is common to both frequencies f_0=307 Hz and f_0=400 Hz that, with increase in acoustical pressure level, the origin of the transition region is displaced toward the leading edge of the plate. For different frequencies however, there are significant differences in the behavior of the curves of the rise in pulsation amplitude. It is evident that the development of turbulent spots for f_0=400 Hz occurs at quite low levels of perturbation in the boundary layer (3.2% and 2.6%), where the lower value of U'/U_1 corresponds to the higher acoustical pressure level. The position of the instability region shown in the upper part of the figure (line 3(2) for f_0=400 Hz) indicates that a type "b" interaction is displayed in this case. It also is evident that, at f_0=307 Hz, the increase in perturbations in the boundary layer, right up to the start of disruption of the wave process occurs in the instability region (line 3(1)) and "direct resonance" is consequently displayed in this case. The disruption of "regular" waves at f_0=307 Hz occurs with significantly higher intensities, and the amplitudes of these oscillations are the higher with Re_t" numbers, the greater the acoustical pressure level (right up to U'/U_1=17% with P=107 dB).

Observations of the nature of the signal on the oscillograph screen at the beginning of the region of transition to turbulence permits it to be stated that, upon exposure to acoustical fields with frequencies f_0=400 Hz and f_0=307 Hz, we encounter different mechanisms of the development of turbulence. At f_0=400 Hz, the modulated "fundamental tone" normal for a natural transition, then subsequent increase of the depth of modulation with the appearance and further development of turbulent spots are seen. Upon exposure to sound with frequency f_0=307 Hz, an increase in amplitude of quite clean, in the broad sense /54
stationary sinusoidal oscillations is observed, with subsequent appearance of high frequency pulsations on the wave "crests." The nature of the disruption of the regular oscillations in this case is similar

to that observed by Obremski and Fejer [22], and it is thus a third type of transition to turbulence. This type of transition is observed when the energy supplied from outside is sufficient for the development of oscillations with preservation of the same frequency right up to the start of disruption of the conditions within the instability region. In those cases when the energy of the outside perturbation is small and the "fundamental tone" fails to develop enough for its destruction to start before reaching the second branch of the neutral stability curve, the transfer of energy occurs to lower frequency packages, and disruption of the ordered processes occurs as a result of the interaction of the low frequencies of one package. Amplitude modulation of the new "fundamental tone" appears in these cases, and turbulent spots then form on the crests of the modulated signal. This kind of disruption of Tollmin-Schlichting waves is observed most often with a quite low level of outside perturbations. A similar development of wave processes upon introduction of two waves was observed in a "model" experiment [13].

We return to [19], and we note two facts without special discussion.

1. Two situations were observed in studies of mutual space correlations $\overline{F'U'}$ (X): a. sound induced hydrodynamic waves (HDW) were observed in the entire range of displacement of the sensor covered by measurement;[4] however, the start of intensive growth of the amplitude of these waves was connected with the central zone of the instability region; the amplitude of the hydrodynamic waves in these cases, right up to the "critical" point, was small and no tendency for it to grow was observed; b. the hydrodynamic waves formed in the central zone of the instability region and were intensely amplified right up to the second branch of the neutral stability curve. In this case, attempts

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[4] For technical reasons, the range of movement of the sensor was not over 1100 mm with minimum distances from the leading edge of 1000 mm and 500 mm.

to isolate hydrodynamic waves ahead of the "critical" point by filtration and subsequent amplification of the signal failed.

2. All attempts to isolate the sound induced hydrodynamic waves at dimensionless frequency $F \cdot 10^6 < 18$, with the utilization of this parameter as both the frequency and the flow velocity proved to be futile in the $1500 < Re^* < 3500$ range of numbers studied. /55

We also note that the longitudinal ±1 dB–±2 dB irregularity of the acoustical pressure level as a function of f_0, noted in [18, 19], was not a random scatter of the measurement results, but was of a regular sinusoidal nature. This indicates that the boundary layer was acted on by both the direct wave directed upstream and the reflected wave. In this case, some disturbance of the frequencies of the direct and reflected acoustical waves because of the presence of a small but finite flow velocity is possible.

Despite many facts which are evidence of a quite clear connection between the parameters of sound, vibrations of the model and perturbations of the flow in the boundary layer, the question of these interactions is not simple or resolved. The attention of theoreticians both in our country and abroad has recently been attracted to the question of the interaction of acoustical fields with shearing flows (see [26] for example). There is however qualitative agreement of theory with experiment so far only for specific cases of interaction in the area of the leading edge. Despite the fact that a number of the experimental facts described above are evidence in favor of other possible types of transformation of an acoustical field to hydrodynamic vibrations in the boundary layer, direct, indisputable proof of other mechanisms of interaction still are lacking.

The answer also remains unclear as to the question of the extent to which vibrations of a plate with displacement amplitude on the order of 10^{-7} m and displacement velocities of 10^{-4} m/s contribute to the formation of hydrodynamic waves with pulsation velocities on the order of 1 m/s, and are not vibrations of a model derivative from the wave processes of the boundary layer. These questions can only be answered by further theoretical and experimental studies.

5. Role of Configuration of Leading Edge of Plate

The conclusions that the role of the leading edge of a plate is important in the conversion of external perturbations to Tollmin-Schlichting waves was expressed in print for the first time in [23], and it was more clearly formulated after the conduct of special experiments in [15, 24]. The experiments described below to study the structure of perturbations in the area of the leading edge in conditions /56 of a low level of external turbulence were performed by the author of these lines independently and in parallel with the authors of [15, 23, 24]. The experiments showed that, with degree of turbulence of the unperturbed flow ε_u=0.03% in the boundary layer of a flat plate with an ellipsoidal inlet section (working surface half axis ratio 2 mm:165 mm, radius of curvature of leading edge r=0.5 mm), powerful wave processes originate with a clearly expressed discrete frequency. The frequency spectra of the longitudinal component of the velocity pulsations are shown in Fig. 22: 1. in the external flow at a distance of 40 mm from the leading edge (ε_u=0.078%); 2. in the boundary layer, X=10 mm ($\overline{U}$=U'/Uδ=0.52; Re"=160); 3. X=0.2 m ($\overline{U}$=0.52; Re"=720). Discrete vibrations with frequency f$\sim$90 Hz are easily seen in curve 2. With increase of the Re number, they are gradually transformed into pulsations with frequencies of 105 and 150 Hz. It is characteristic that, for the same plate, discrete vibrations with almost the same frequency are easily seen at the leading edge and in the velocity pulsation spectra of the boundary layer with significantly higher intensity of incoming flow turbulence (see Fig. 13 of the present work).

The nature of the change in integral value of the velocity pulsations along the plate is shown in Fig. 23a (curve 1, $\varepsilon_{u\infty}$=0.03%; $\overline{U}$=0.052=const; 2. $\varepsilon_{u\infty}$=0.7%; $\overline{U}$=0.45=const). The abrupt increase in value of U' in the immediate vicinity of the leading edge for curve 1

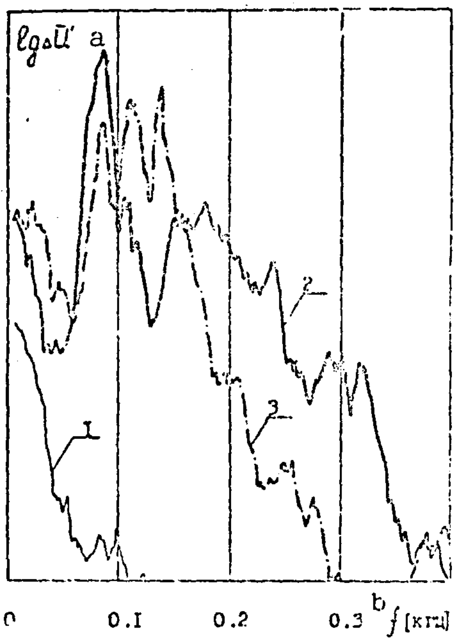

Fig. 22.

Key: a. log Ū'
b. f, kHz

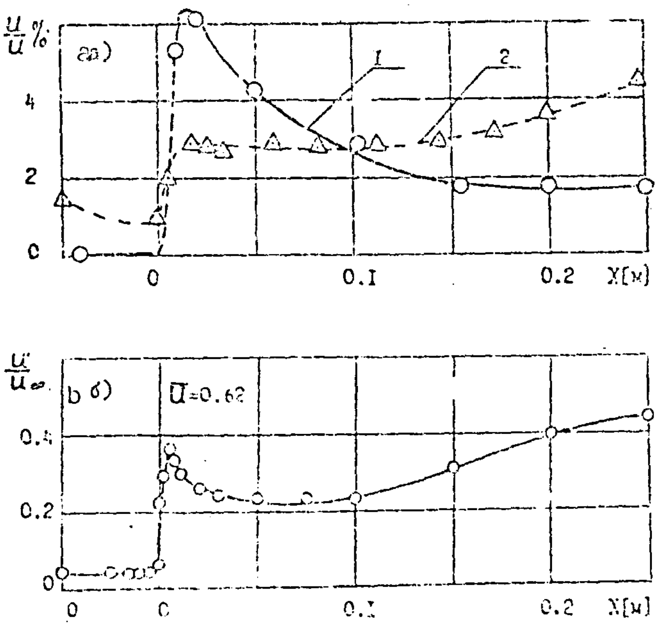

Fig. 23.

(by approximately two orders of magnitude), with a subsequent monotonic decrease in pulsation intensity attracts attention. With increase in turbulence of the flow, the amplification "coefficient" of the pulsations is much less, but an increase in intensity of the perturbations also is accompanied by the isolation of a discrete pulsation package of almost the same frequency. The leading edge of the plate thus operates in these conditions as a selective amplifier. We note that the intensity of the velocity pulsations in the initial sections of the boundary layer is half as much with increased turbulence as with low turbulence. At the same time, an increase in pulsation level with distance from the leading edge is clearly expressed for curve 1 and, for curve 2, an increase in the integral pulsation intensity. The increase of perturbations with increased turbulence is easily examined from the velocity pulsation spectra in Fig. 13, and it is connected with the peculiarity of the transition to turbulence with the stage of development of the Tollmin-Schlichting waves bypassed. It also is evident from Fig. 13 that the discrete frequency package, which is distinctly expressed at the leading edge, plays no part in the phenomena of transition to turbulence and, decreasing in amplitude with increase in the Re number, it is gradually dissolved into a continuous spectrum. We also note that subsequent development of oscillations with frequency f=150 Hz, which is displayed as a result of degeneration of the "fundamental tone" with f_0=90 Hz (curve 3 in Fig. 22), was followed in detail in Section 2 (Figures (11) and (12)), where it was shown that these vibrations arising at the leading edge play only an auxiliary role in the transition phenomena. /58

Of what in our opinion, does the mechanism of the abrupt increase of velocity pulsations at the leading edge of the plate consist?

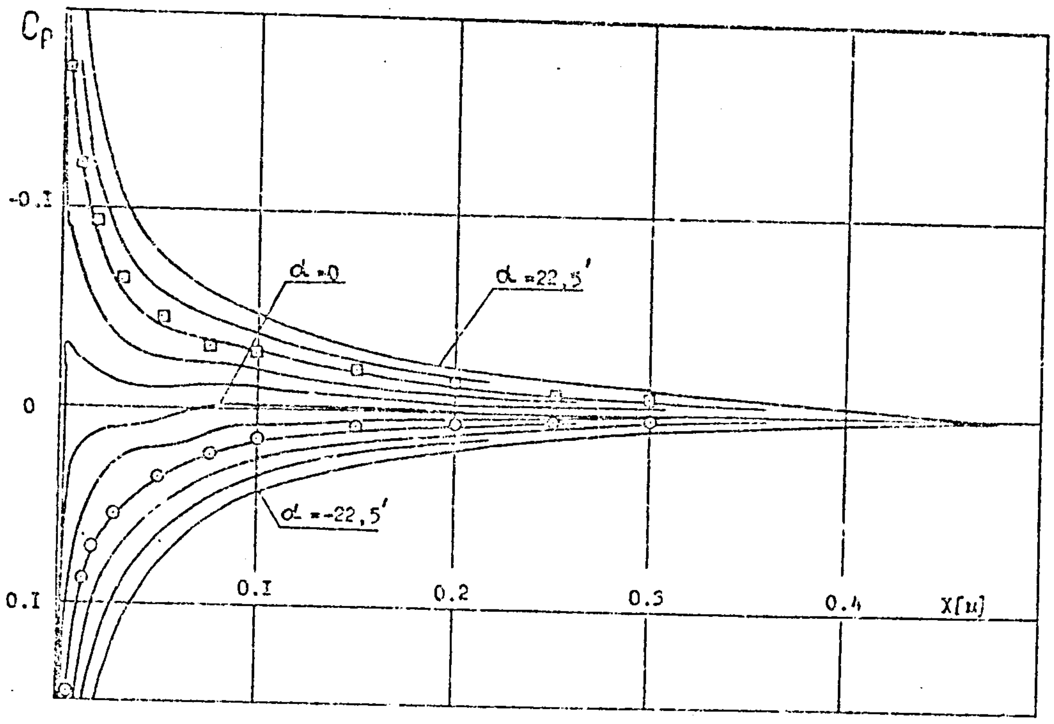

Fig. 24.

We turn again to data of the experiment on distribution of pressure in the initial sections of the plate compared with the results of theoretical calculation [11]. The results of theoretical calculation of the distribution of the static pressure in the initial section of a given plate with change in angle of incidence in the $22.5' > \alpha > -22.5'$ range with $\Delta\alpha = 4.5'$ steps are presented in Fig. 24. The results of the experiment which correspond to limiting curves 1 and 6 in Fig. 5 are plotted with the symbols. It is evident that the local angle of approach of the flow to the plate changed between $-13.5'$ and $+9'$ in the conditions of the experiment, from which it follows that the nature of the pressure distribution in the vicinity of the leading edge is extremely sensitive to negligible changes in the angle of incidence of the plate or, which is the same, to variations of the reentry angle of the flow to the plate. Further, estimates of change of the instantaneous velocity vector of the flow as a result of the transverse component of the velocity pulsations, even with a very low intensity of incoming flow turbulence, show that changes of the angle of approach of the flow to the plate are on the order of magnitude of a few minutes (for $U'/U = 0.07\%$, $\Delta\alpha = 2.4'$). It follows from the Fig. 24 data that, for X=10-20 mm, such a change of the angle of incidence corresponds to $\Delta Cp = (Pi - Pk)/q \approx 0.02$, from which $\Delta U/U = \sqrt{\Delta Cp} \approx 0.15$. In order of magnitude, this corresponds to the experimentally observed velocity pulsations in the boundary layer. Based on this, the mechanism of amplification of the velocity fluctuations in the area of the leading edge appears to be the following: the transverse component of the velocity pulsations (normal to the plane of the plate) of the incident flow induces fluctuations of the local angle of approach of the flow. This leads to redistribution in time of the pressure (consequently velocity) on curvilinear sections of the plate with simultaneous amplification of the velocity pulsation amplitudes. In /60 this case, the "coefficient" of gain of the velocity pulsations should be connected with an angular measure of pulsations of the point of flow and consequently, with the parameters of the transverse components of velocity pulsations incident on the edge and the radius of the intake edge, as well as with the parameters [words illegible] to the plate.

Measurements of the pulsation intensity on the initial section of the plate (obtained with b:a=1:33) with leading edge radius r=1 mm, performed with a low level of perturbations (ε_u=0.03%) and preservation of the smooth converging tube distribution of static pressure in the intake sections, showed that the "coefficient" of gain was reduced by an order of magnitude (Fig. 23b) from that of curve 1 in Fig. 23a. This confirms the correctness of the positions expressed.

The quasistationary mechanism of conversion of the vertical velocity pulsation component to a longitudinal pulsation component in the boundary layer formulated above corresponds qualitatively to the results and conclusions of the experiments and theoretical developments in [15, 23, 24]. Based on our mechanism however, the decisive role belongs to the specific configuration of the leading edge, while the conclusions, calculations and substantiations in [15, 23, 24] were made for a plate with a "sharp" leading edge ($r \ll \lambda$), where the actual configuration of the intake section plays no part in this case.

It is evident that the quasistationary mechanism of transformation of the transverse components of pulsation of the external flow to longitudinal fluctuations of the flow in the boundary layer will act similarly both in transverse vibrations of the plate [23] and in the imposition of a transverse acoustical field [24].[5] It must be emphasized that the action of the abovementioned mechanism concerns conditions of a low level of turbulence which is characteristic of a low frequency (longwave) spectrum while, with increased turbulence with a broad spectrum of vortex system scales, transformation of perturbations at the leading edge is more complex.

There also is no doubt that the analysis conducted is built up on spotty results of an exploratory experiment which does not yet

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[5] It should be noted that, in [25], attention is drawn to the possibility of operation of cylindrical leading edges as a "amplifier" of velocity pulsations in conditions of exposure to a transverse acoustical field.

answer all the questions. The greatest vagueness is connected with the conditions of origination and regularities of behavior of vibrations of a discrete frequency in the initial sections of the boundary layer. There is no doubt that these regular perturbations are self excited and connected with the leading edge configuration. It can be thought that the feedback mechanism of the self exciting process is acoustical in this case. Only further experiments however can confirm the correctness of such hypotheses. The main and, to be sure, undoubted conclusion which flows from the abovementioned is that the acute sensitivity of the pressure gradients at the leading edge of real models with a specific surface curvature to the position of the point of flow determines the mechanism of transformation of transverse flow fluctuations of any nature to longitudinal velocity fluctuations in the boundary layer, with simultaneous amplification of these fluctuations.

6. Effect of Incident Flow Velocity

The disagreement of the results of the experiments in [1] and [5] is explained by both the individual features of the nature and structure of the flow perturbations in different wind tunnels and, as well, by the methods of change of intensity of the turbulence. While the value of ε was changed in [1] with a set of given grids in the mixing chamber and the experiments to determine the $Re_t(\varepsilon)$ number were performed at constant flow velocity, in the tests of V.M. Filippov [5] (just as basically of the author of the present work), functions $Re_t(\varepsilon)$ were obtained with constant conditions in the mixing chamber, with change in the degree of turbulence by increase of the flow velocity. If the data of V.M. Filippov and our results are presented in the form of function $Re_t(U)$, the disagreement observed in Fig. 1 is significantly reduced (Fig. 25: 1. results of author; 2. data of Filippov), and they can be explained by some difference in pressure distribution in the vicinity of the leading edge (Fig. 7). It must be noted that our results and the data of Filippov were obtained in identical wind tunnels but on different models of the plates and auxiliary structures located in the working section of the wind tunnel. Precisely this latter situation led to differences in the dependence of the integral turbulent intensity on the flow velocity.

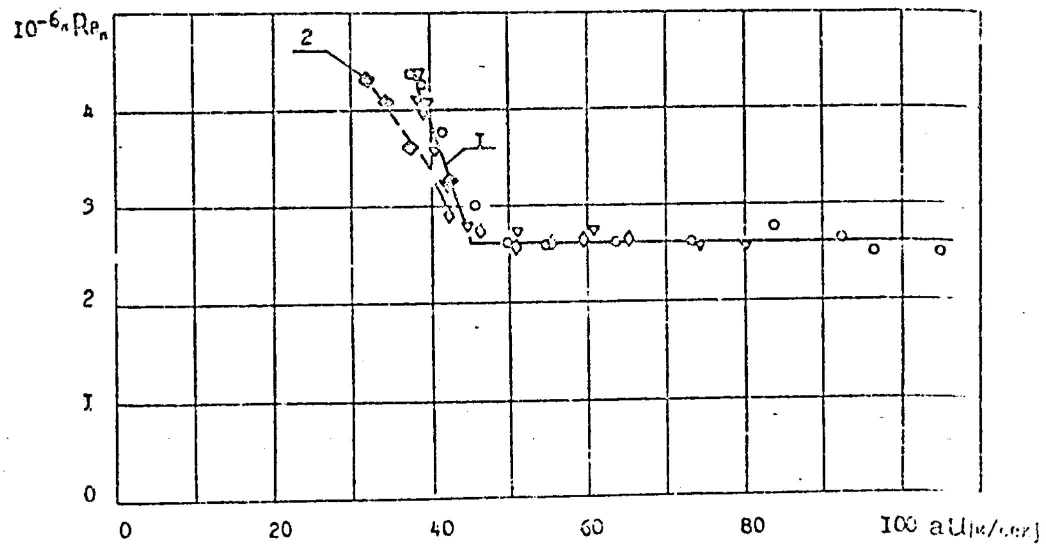

Fig. 25.

Key: a. U, m/s

At the same time, the coincidence of our results with the data of V.M. Filippov when they are presented in $Re_t(U)$ coordinates (Fig. 25) with the significant difference in Fig. 1 is evidence that the /64 primary effect of perturbations of the flow on the state of the boundary layer is not connected, as is generally accepted, with the integral value of the degree of turbulence. The vibrational energy with frequencies which correspond to those internal areas of the theoretical instability region where the rate of increase of perturbation amplitude is the greatest has a more significant effect on the development of perturbations in the boundary layer.

In comparing the power spectra of the external turbulence in their conventional representations (Fig. 26a) for different flow velocities, it can be seen that, with increase in flow rate, the spectra become more filled in both amplitude and frequency. Presentation of the same spectra in $E=f(\omega\nu/U^2)$ coordinates has the result that, with increase in flow velocity, the external perturbations encompass a smaller and smaller range of dimensionless frequencies $F=\frac{\omega\nu}{U^2}$ and are displaced downward outside the limits of the theoretical instability region (Fig. 26b). In Fig. 26, curve 1 corresponds to U=13.1 m/s, 2 to U=30.2 m/s, 3 to 40.6 m/s and 4 to 51.3 m/s; the letter e designates the theoretical lines of the neutral stability curve in $Re^*=f(\omega\nu/U^2)$ coordinates.

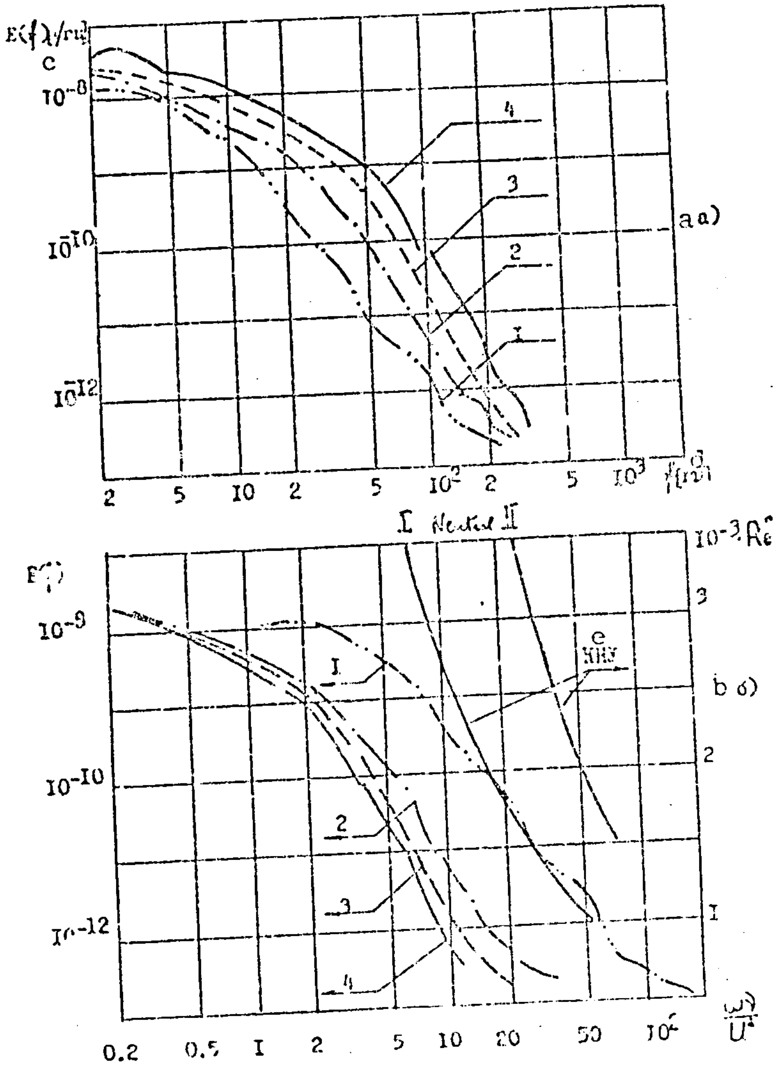

Fig. 26.

Key: c. E(f), Hz^{-1}
d. f, Hz
e. Neutral stability curve

The data in Fig. 26b permit explanation of the effect of stabilization of the Re_t numbers in our experiments with $\varepsilon>0.08\%$ (Fig. 1) or U>45 m/s (Fig. 27), by displacement of the actual power spectra of the external turbulence with increase in velocity outside the "active" range of dimensionless frequencies, which are most sensitive to external perturbations.

In summarizing the abovementioned, the following main conclusions can be noted.

1. The structure of the flow perturbations in a laminar boundary layer (LBL) in all stages of its development under "natural" conditions, with a low level of external perturbations, is a complex conglomerate of wave processes. The behavior of the perturbations basically obeys the conclusions and predictions of stability theory.

2. With a relatively low level of external perturbations, a package of discrete frequencies is isolated in the laminary boundary layer, which is responsible for the transition to turbulence, to which similar isolated frequency packets in the external perturbation spectra correspond.

3. Depending on the intensity of the turbulence of the incident /65 flow, the energies of the package of discrete fluctuations of the external perturbations which most strongly affect the wave process in the laminary boundary layer, as well as on the position of the dimensionless frequency of these perturbations relative to the "active" zones of the theoretical instability region in the "natural" transition, three different types of disruption of laminar conditions are distinguished:

a. disruption of the Tollmin-Schlichting waves as a result of the interaction of several wave processes which belong to the instability region, characterized by a clearly expressed modulation of the "fundamental tone" with the appearance of turbulent spots on the crests of the modulated signal;

b. disruption of the Tollmin-Schlichting waves in a regular single wave condition;

c. disruption of the laminar state with the development of a continuous spectrum of vibrations, bypassing the stage of formation and development of Tollmin-Schlichting waves.

4. Acoustical perturbations play an important role in the development of perturbations in a laminar boundary layer. Their interaction with the laminar boundary layer occurs only in a specific "active" frequency band. The mechanism of this interaction is not completely clear, since a number of experimental facts cannot be explained at this stage by either existing theoretical work or the hypothesis of the role of the leading edge.

5. The leading edge of the models is of great importance in the mechanism of transformation of external perturbations to velocity fluctuations in a laminar boundary layer, even with a low level of perturbation of the incident flow. The acute sensitivity of the pressure gradients in the initial sections of the laminar boundary layers of real models to the location of the point of flow has the decisive role here. In these conditions, the leading edge transforms transverse flow fluctuations to longitudinal velocity pulsations in the laminary boundary layer and plays the part of selective amplifier. However, the perturbations which originate in these conditions (Tollmin-Schlichting waves) do not always play a decisive role in phenomena of the transition to turbulence.

6. The position of the transition region in conditions of low perturbation levels is not determined by the integral value of the degree of turbulence of the flow. Individual packets of external perturbations with dimensionless frequencies which correspond to the "active" zones of the instability region, which depend on both the perturbation frequency and on the flow velocity, are of greater importance.

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