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The influence of the low free stream perturbations on the condition of laminar boundary layer(*)

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THE RESULTS of experiments on the study of the frequency spectrum of perturbations in the laminar boundary layer and the transition phenomena are analysed. The experiments were carried out on a flat plate in the low-turbulence wind tunnel for low subsonic speeds at the maximum Reynolds number of transition $Re_{tr} = 4.35 \cdot 10^6$. The frequency spectra of the velocity fluctuations in the boundary layer are compared with the velocity components and the pressure free stream fluctuations, and also with the spectra of the flat plate vibrations. It is shown that the fluctuations in the boundary layer are connected with the discrete modes in the spectrum of the free stream perturbations at the free stream turbulence intensity being equal to $\varepsilon < 0.1\%$. It is also shown that in the case when the free stream is superposed on the longitudinal sound field of the discrete frequency, the stationary, in a wide sense, hydrodynamic waves of the same frequency arise under certain conditions. A region of existence of the intensively developing hydrodynamic waves induced by the sound is determined. It is found that at a number $Re < Re_{tr}$ the laminar boundary layer appears to be very sensitive to the sound oscillations in a certain "active" frequency band, and various kinds of interactions can be observed. The results of the study of the Re_{tr} numbers dependence on the level of the acoustical pressure for the arbitrary chosen frequencies of the "active" range differ from the data by Spangler and Wells. The correlation between the sensitivity of the boundary layer to the sound frequency and the forced resonance frequencies of the plate vibrations is noted. The dependence of Re_{tr} on the turbulence degree of the free stream at $\varepsilon < 0.15\%$ found experimentally differs considerably from the data by Schubauer, Skramstad and other authors. The analysis of this discrepancy is also presented.

Przeanalizowano wyniki doświadczeń nad widmem częstości zakłóceń w laminarnym przepływie przyściennym i nad zjawiskami przejścia. Doświadczenia wykonywano na płaskiej płytce w tunelu aerodynamicznym przy niskich prędkościach poddźwiękowych, w których maksymalna wartość liczby Reynoldsa wynosiła $Re_n = 4,35 \cdot 10^6$. Widma częstości fluktuacji prędkości w warstwie przyściennej porównuje się ze składowymi prędkości i z fluktuacjami ciśnienia strumienia swobodnego, a także z widmami częstości drgań płaskiej płytki. Pokazano, że fluktuacje w warstwie przyściennej są związane z dyskretnymi modami widma zakłóceń strumienia swobodnego przy intensywności turbulencji strumienia osiągającej $\varepsilon < 0,1\%$. Pokazano również, że gdy strumień swobodny superponuje się z podłużnym polem dźwiękowym o dyskretnej częstości, powstają w pewnych warunkach fale hydrodynamiczne o tej samej częstości. Określono obszar istnienia intensywnie rozwijających się fal hydrodynamicznych wywołanych przez dźwięk. Stwierdzono, że przy ustalonej wartości liczby $Re < Re_n$ laminarny przepływ przyścienny staje się bardzo wrażliwy na drgania dźwiękowe w pewnym "aktywnym" pasmie częstości i można wtedy zaobserwować wiele typów współdziałania. Wyniki badań nad zależnością liczb Re_n od poziomu ciśnień poddźwiękowych przy dowolnie dobranych częstościach obszarów "aktywnych" różnią się od wyników podanych przez Spanglera i Wellsa. Stwierdzono istnienie związku między wrażliwością warstwy przyściennej na częstość dźwięku a częstościami drgań rezonansowych płytki. Zależność Re_n od stopnia burzliwości strumienia swobodnego przy $\varepsilon < 0,15\%$ (wielkość wyznaczona eksperymentalnie) różni się w sposób istotny od rezultatów Schubauera, Skramstada i innych autorów. Przedstawiono również analizę tych niezgodności.

Проанализированы результаты экспериментов по исследованию спектров возмущений в ламинарном пограничном течении и по переходным явлениям. Эксперименты проведены на плоской пластине в аэродинамической труое при низких дозвуковых скоростях, в которых максимальное значение числа Рейнольдса равнялось $Re_n = 4,35 \cdot 10^6$. Спект-

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ры частот флуктуации скорости в пограничном слое сравниваются со спектрами пульсации скорости и с флуктуациями давления свободного потока, а также со спектрами частот колебаний плоской пластинки. Показано, что флуктуации в пограничном слое связаны с дискретными модами спектра возмущений свободного потока при интенсивности турбулентности потока $\varepsilon < 0{,}1\%$. Показано тоже, что когда свободный поток взаимоцействует с продольным звуковым полем с дискретной частотой, возникают в некоторых условиях гидродинамические волны с той же самой частотой. Определена область существования интенсивно развивающихся гидродинамических волн, вызванных звуком. Установлено, что при постоянном значении числа Re $< \mathrm{Re}_{н}$ ламинарное пограничное течение становится очень чувствительным к звуковым колебаниям в некотором „активном" диапазоне частот и можно тогда наблюдать много типов взаимодействия. Результаты исследований зависимости чисел $\mathrm{Re}_{н}$ от уровня звукового давления, при произвольно подобранных частотам „активных" областей, отличаются от результатов приведенных Спанглером и Веллсом. Обнаружено существование связи между чувствительностью пограничного слоя к частоте звука и частотами резонансных колебаний пластинки. Зависимость $\mathrm{Re}_{н}$ от степени турбулентности свободного потока при $\varepsilon < 0{,}15\%$ отличается существенным образом от результатов Шубауэра, Скрамстада и других авторов. Представлен тоже анализ этих расхождении.

IT IS COMMON knowledge that the free stream perturbations in the low subsonic velocities region influences the position of the transition region from the laminar to the turbulent boundary layer. The results of SCHUBAUER and SKRAMSTAD's experiments [1], connected with the definition of the dependence between the transition Reynolds number (Re_{tr}) and the free stream turbulence intensity (ε) are widely known and used in manuals and monographs. VAN DRIEST and BLUMER [2] using these data and other ones proposed a semi-empirical formula for the transition Reynolds number dependence from the turbulence degree. Several other works were devoted to this problem. However, some later experiments showed that the dependence $\mathrm{Re}_{tr}(\varepsilon)$ at low turbulence intensity is not a simple one.

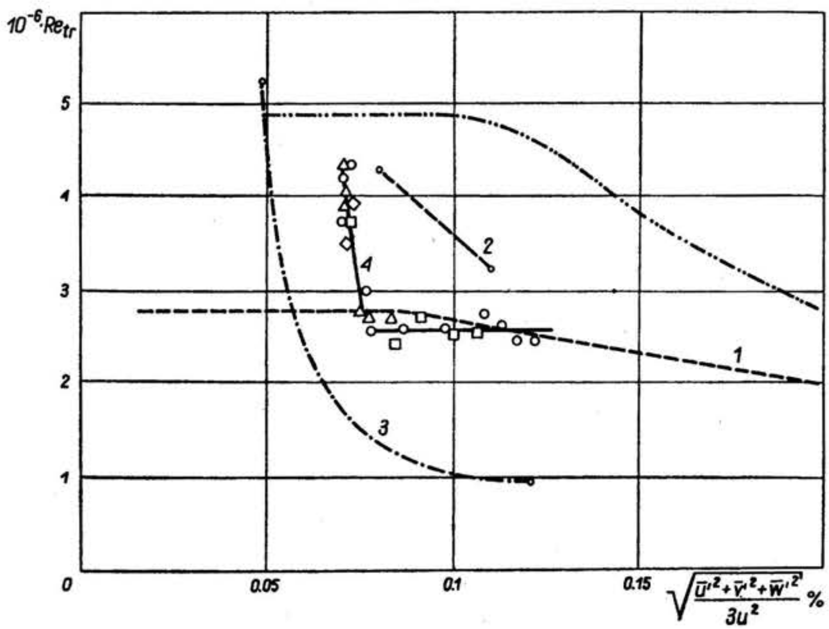


FIG. 1.

Some experimental dependencies between the transition Reynolds number and the low free stream turbulence degree

$$\varepsilon = \frac{1}{U_1}\sqrt{\frac{1}{3}(\overline{u'^2}+\overline{v'^2}+\overline{w'^2})}$$

are shown in Fig. 1. This figure presents the data obtained by various authors: *1* — SCHUBAUER and SKRAMSTAD [1], *2* — PHILIPPOV [3], *3* — SPANGLER and WELLS [4], *4* — our results. The latter were obtained on a flat plate the length of which was 3.9 m by using the low turbulence wind tunnel T-324 of the Institute for Pure and Applied Mechanics of the Siberian Branch of the USSR Academy of Sciences.

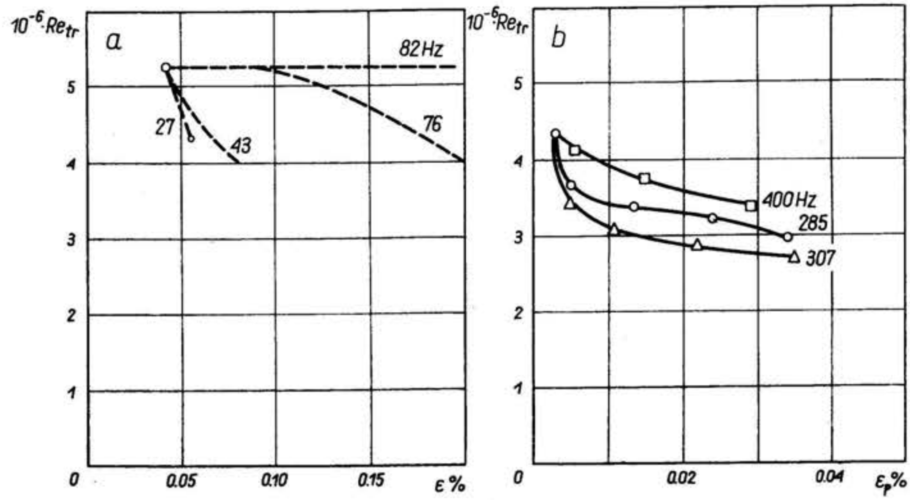


FIG. 2.

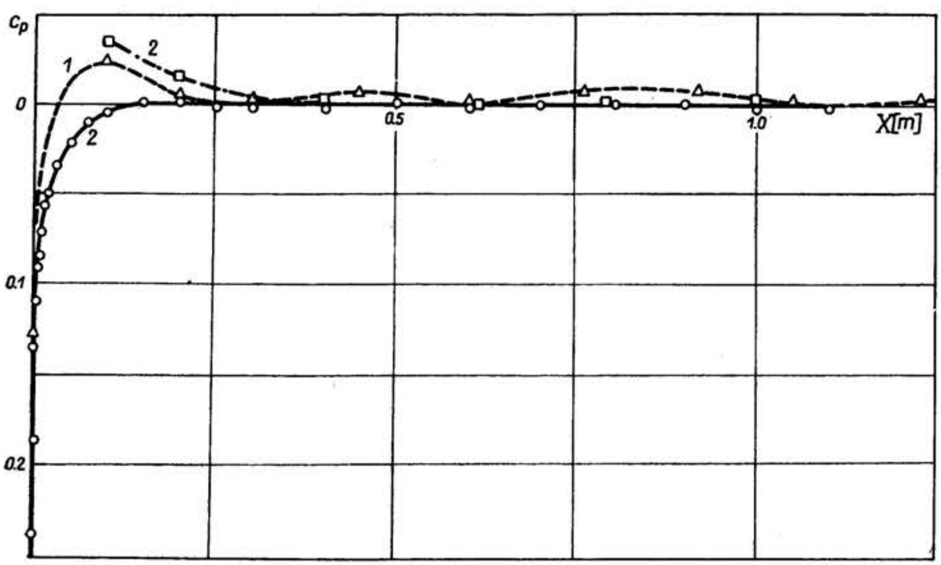


FIG. 3.

The dependence of Re_{tr} versus the level and frequency of acoustic oscillations f_0 are shown in Fig. 2: a) our results, b) SPANGLER and WELLS' data [4]. It is useful to note that only Schubauer and Skramstad, Philippov's and our experiments were carried out on a flat plate with a well-known pressure distribution and a zero longitudinal pressure gradient (Fig. 3). The results presented in Figs. 1 and 2 allow us to draw the next conclusion: the dependencies $Re_{tr}(\varepsilon)$ and $Re_{tr}(\varepsilon_p, f_0)$ are not universal ones, at least at low perturbation intensities and hence, it is incorrect to search for the interaction between the transition Reynolds numbers and the summarized characteristics of perturbations. On the other hand, the same data allow us to state several problems:

1. How can we explained a "shelf" Re_{tr} = const in the Schubauer and Skramstad's results when $\varepsilon < 0.1\%$?

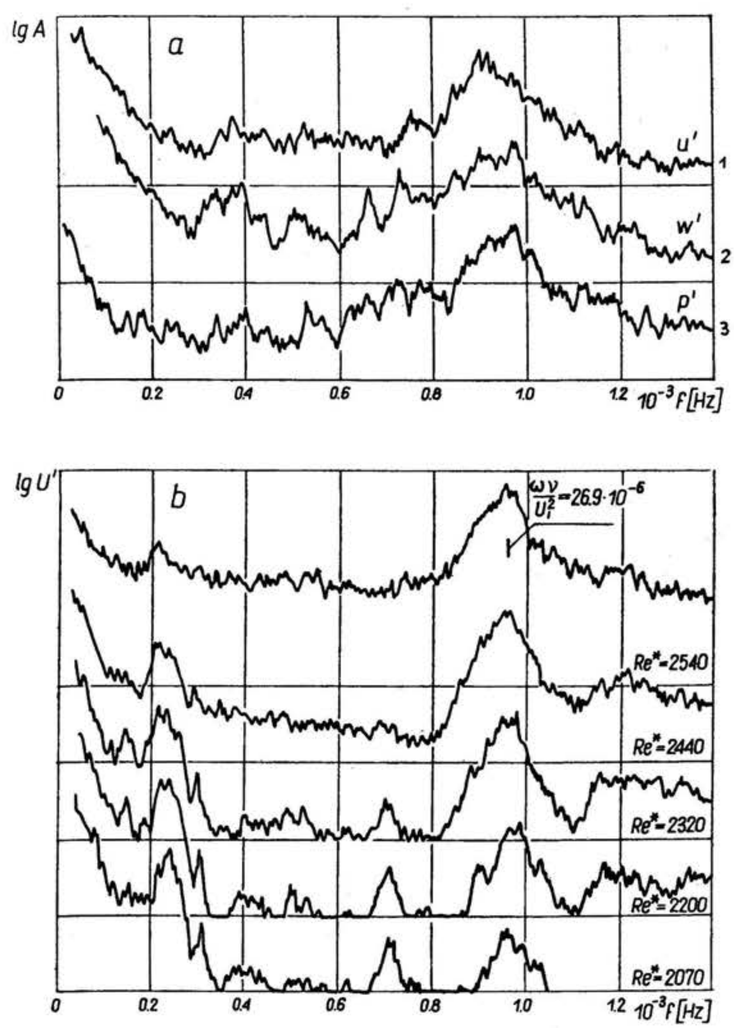


FIG. 4.

2. What are the resons for the essential differences between the results obtained by Schubauer and Skramstad, Philippov and us?

3. What are reasons of the discrepancies in the dependencies between Re_{tr} and the sound frequency f_0 in the results obtained by us and Spangler and Wells?

4. Why does the "shelf" (Re_{tr} = const) appear in our results when $\varepsilon > 0.07\%$?

We can answer these questions by examining the experimental data on the frequency structure of the free stream perturbations, boundary layer fluctuations and some other results. Comparison of the spectral energy distribution of velocity fluctuations at different stages of laminar boundary development (Fig. 4a) with the power spectral density of the free stream perturbations (Fig. 4b) (there, *1* is a longitudinal component of the velocity fluctuations — u'; *2* is a lateral one — w' and *3* represents the pressure perturbations — p') allows us to draw attention to the following facts:

1) In the case when the free stream perturbation levels are low, a group of frequencies with the predominating amplitudes are always present in the laminar boundary layer. The central frequency of this frequency group is called "a main tone". The "main tone" amplitude increases by increasing the Reynolds numbers.

2) In the boundary layer, the power density spectrum of velocity fluctuations contains, apart from a "main tone", higher discrete frequencies which reflect the nonlinear effects, and also the low frequencies in a continuous spectrum.

3) The frequency groups in the free stream perturbation spectrum correspond to one "main tone" of the laminar boundary layer velocity fluctuations (Fig. 4b).

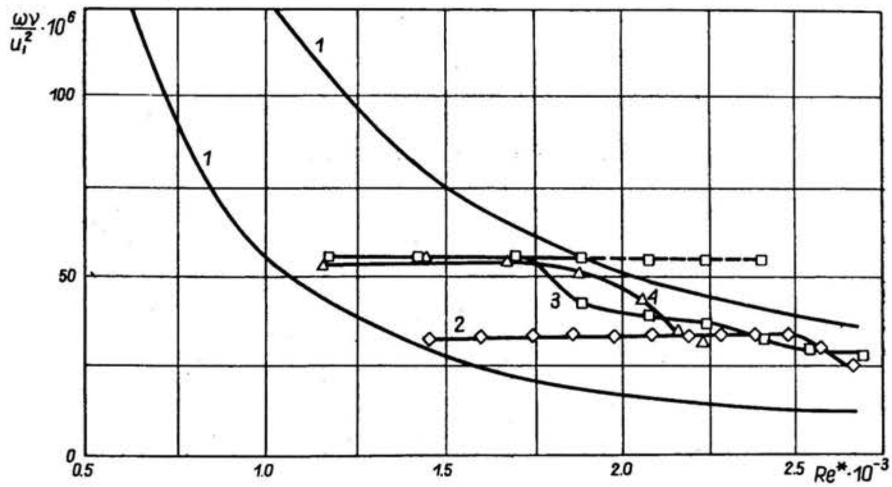


FIG. 5. *1* — the curve of the neutral stability, *2* — $U = 52$ m/s, *3* — $U = 41.2$ m/s, $\varepsilon_u = 0.026\%$, *4* — $U = 40.5$ m/s, $\varepsilon_u = 0.41\%$.

4) The "main tone" fluctuations develop in the theoretically unstable region only (Fig. 5), changing its frequency near the second branch of a neutral curve. A "main tone" destruction with the turbulence spots production takes place always inside the instability region.

5) The amplitudes of low frequency oscillations increase in the continuous spectrum near the transition region. Their interactions with the "main tone" lead to the destruction of the regular waves and the appearance of turbulence spots.

These facts are based on a detailed analysis of the boundary-layer velocity fluctuations spectrograms at different free stream states (different velocity — U_1 and turbulence intensity — ε under the condition of "natural" transition). Thus we can draw the following conclusions:

1) At low intensity of the free stream perturbations the "main tone" generation and its development takes place under the influence of the discrete tone of the free stream perturbations whose energy is much smaller than their total energy.

2) During the process of wave development which leads to the appearance of turbulent spots, the interaction between the "main tone" and low frequency fluctuations is of essential importance.

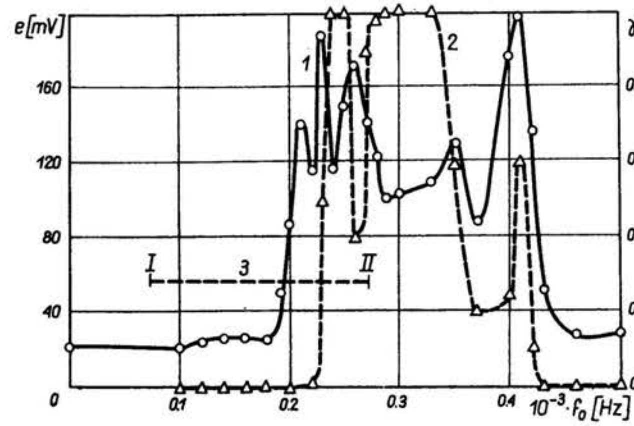


FIG. 6. Re $= 3.83 \cdot 10^6$, $P = 102 \pm 2$ db.

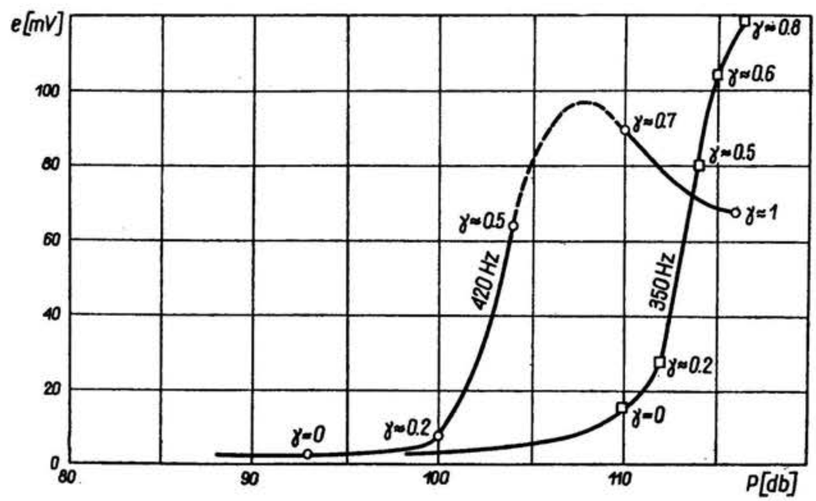
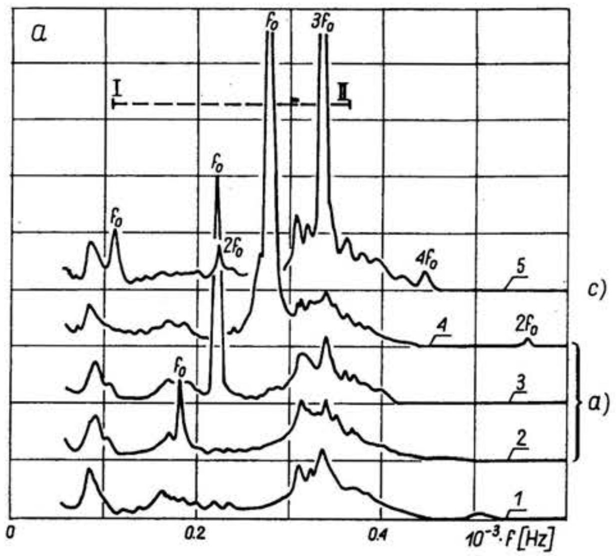


FIG. 7. $U = 30$ m/s, Re $= 2.03 \cdot 10^6$.

The latter conclusion was confirmed by theoretical investigations performed by A. G. VOLODIN and M. B. ZELMAN [5] and by model experiments carried out by YU. S. KACHANOV, V. V. KOZLOV, V. YU. LEVCHENKO [6].

The physical aspects of the influence of acoustic perturbations on the boundary layer state are a matter of a special interest. Our experiments on a flat plate [7, 8] have shown that the laminar boundary layer under the condition of Re = const < Re_{tr} and a fixed acoustic pressure level is very sensitive to the discrete sound frequency in the definite "active" band width associated with the theoretical instability region 3 (Fig. 6). However,



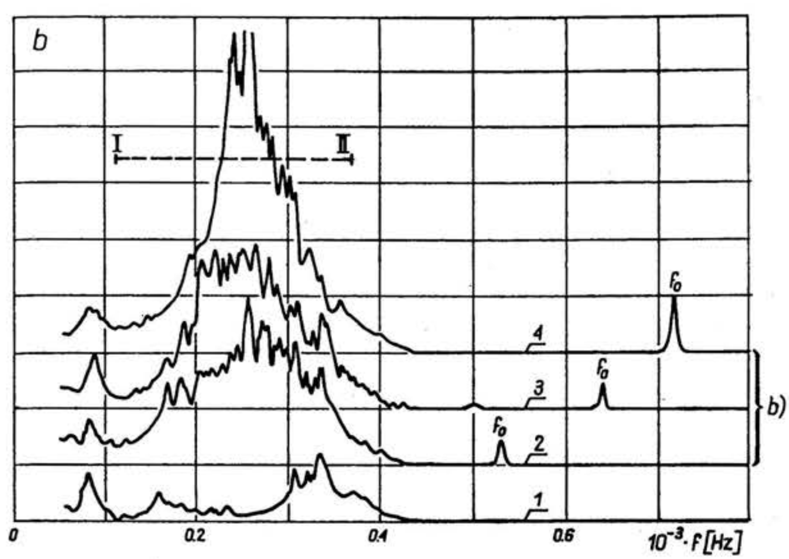


FIG. 8.

the sharp resonance on certain acoustic frequencies as noted in SPANGLER and WELLS' [4] and VLASOV and HINIEVSKY's [9] experiments was not observed. When changing the sound pressure level of the plane longitudinal acoustic field of discrete frequency from the "active" band width, one can easily obtain any boundary layer condition: from a pure laminar regime, to a well-developed turbulent one, passing through all the stages of the intermittency factor γ changing in the transition region (Fig 7).

The frequency analysis of the stream perturbations in the laminar boundary layer under the condition of the acoustic field with various discrete frequencies f_0 from the "active" band and Reynolds number smaller than Re_{tr} (Fig. 8) shows that four types of interactions dependent on the frequency position which is relative to the theoretical instability region I-II can be distinguished: a) "direct" resonance, b) "induced" resonance, c) "direct" resonance with one of the harmonics of acoustic frequency f_0, d) "direct" resonance at low sound pressure level transforming into a form of induced resonance with the increase of sound pressure.

The results of these experiments allow us to draw the conclusion that the "shelf" $\mathrm{Re}_{tr} = \text{const}$ under the condition of $\varepsilon < 0.1\%$ obtained by Schubauer and Skramstad is connected with a high sound pressure level. This level ranges from 105 up to 107 db in the wind tunnel of the National Bureau of Standards and the frequency spectrum contains the harmonics from an "active" band. Hence, at the intensity of turbulence $\varepsilon > 0.1\%$, the change of vorticity mode affects the Re_{tr}, but at $\varepsilon < 0.1\%$ the change of vorticity mode does not influence the position of the transition region since the acoustic mode played a principal part. Its intensity and the power spectral density remained constant. This is the answer to the first question.

Space-time and cross-correlation investigations (Fig. 9) between free stream pressure fluctuations and boundary layer oscillations have shown that under the condition of a "direct" resonance the steady, in a wide sense, hydrodynamic waves induced by the

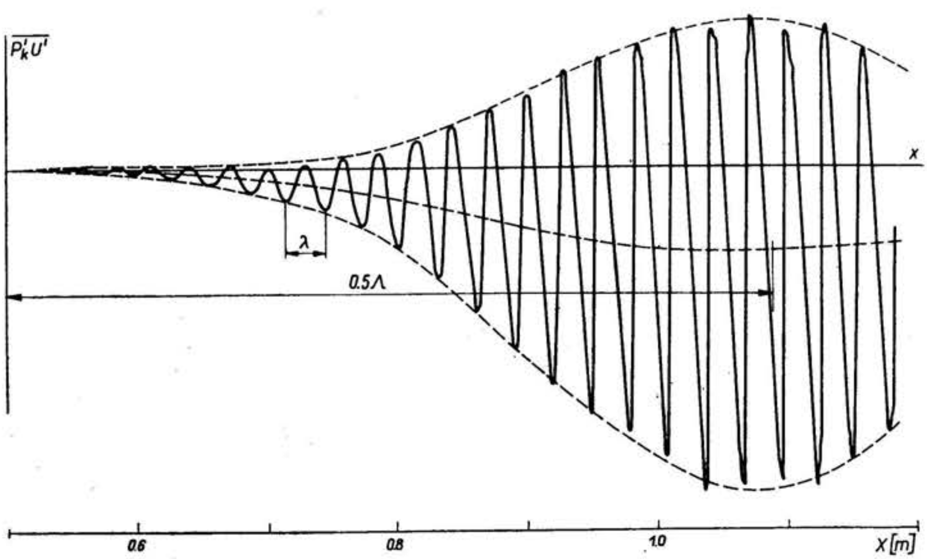


FIG. 9.

sound appear and develop intensely in the laminar boundary layer. The region of existence of these waves lies between the center line and the second branch of the theoretical curve of neutral stability calculated in accordance with the linear theory (Fig. 10).

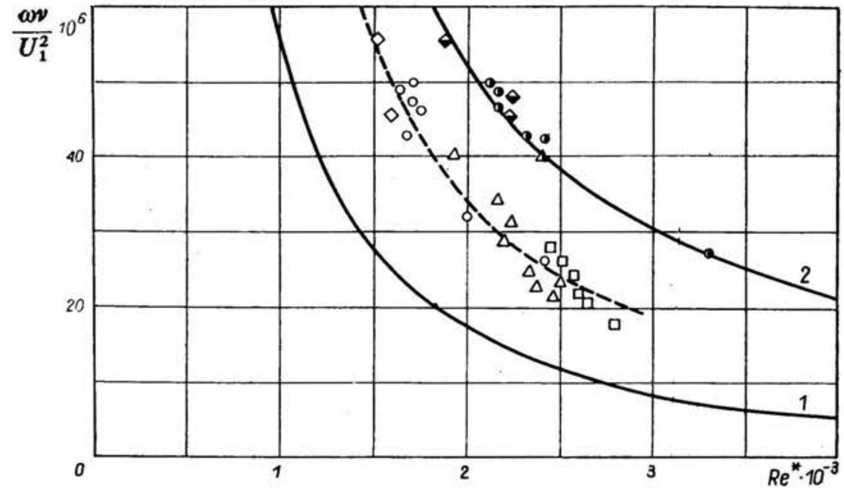


FIG. 10.

Comparison between the amplitude — frequency responses of the flat plate vibrations under the acoustic effect (Fig. 11) and the dependence $Re_{tr}(\varepsilon, f_0)$ for three arbitrarily chosen sound frequencies from an "active" band (Fig. 2) shows that the distortion of regularity in the dependence $Re_{tr}(f_0)$ under the condition of a constant sound pressure level correlates with the stimulated plate vibrations. We can suppose that the sharp resonance of boundary layer sensitiveness to the particular frequency described in SPANGLER

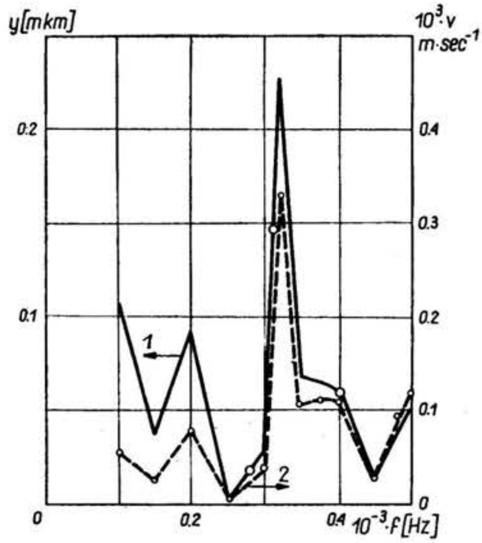


FIG. 11.

and WELLS' paper [4] is connected with the eigenfrequency of the experimental installation (the vibrations or the stationary waves). A similar conclusion was drawn in [10] by V. V. KOZLOV *et al.* However, the problem of the acoustic influence on the boundary layer condition and the role of correlation between a plate or installation vibration response and boundary layer perturbations is not simple and the following questions can be formulated.

1) How can free stream pressure fluctuations having a wave length exceeding 1 m ($\lambda > 1$ m) be transformed into hydrodynamic waves with a length of about 30 or 40 mm ($\lambda = 30$–40 mm) and with the frequency f_0 preserved?

2) How can a plate vibration with an amplitude approximately equal to 10^{-7} m and a displacement velocity of about 10^{-4} m/s promote hydrodynamic waves with a fluctuation velocity of about 1 m/s?

The forthcoming theoretical and experimental studies should answer these questions.

Now we shall try to give an answer to the questions number 2 and 3 formulated above. The reasons of the discrepancy between the results of Schubauer and Skramstad, Philippov and ours are as follows:

1) The perturbations have specific features in different installations. They appear in the differences of acoustic and vorticity modes and in the power spectral density discrepancies.

2) Differences exist in the turbulence intensity variation method. Schubauer and Skramstad varied the turbulence level by using different screens and performed the experiments under the condition of a constant free stream velocity ($U_1 \simeq 30$ m/s); our results, however, as well as Phillipov's were obtained with the fixed screens, and the velocity increase was used to vary the degree of turbulence.

If we plot our data and Phillipov's results in the dependence $\mathrm{Re}_{tr}(U_1)$ (Fig. 12), then

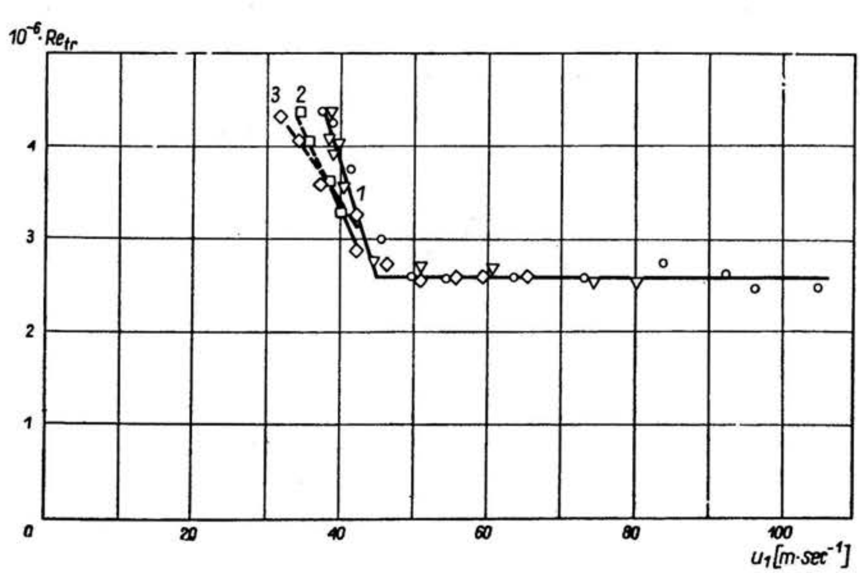


FIG. 12.

the discrepancies presented in Fig. 1 can be essentially decreased and explained by some difference in the pressure gradient distribution near the flat plate leading edge (see Fig. 3 and [11]). It is interesting to note that our results and Phillipov's data were obtained in the identical wind tunnel, but with a different plate and auxiliary constructions placed in the test section. This leads to the discrepancy in the dependence of the turbulent intensity level from the free stream velocity.

The coincidence of our results with Phillipov's data in the coordinates $\mathrm{Re}_{tr}(U_1)$, despite the essential discrepancy in the coordinates $\mathrm{Re}_{tr}(\varepsilon)$, indicates the influence of principal perturbations on the laminar boundary layer condition which is not connected, as it is generally accepted, with the total free stream turbulence intensity. The energy of the same

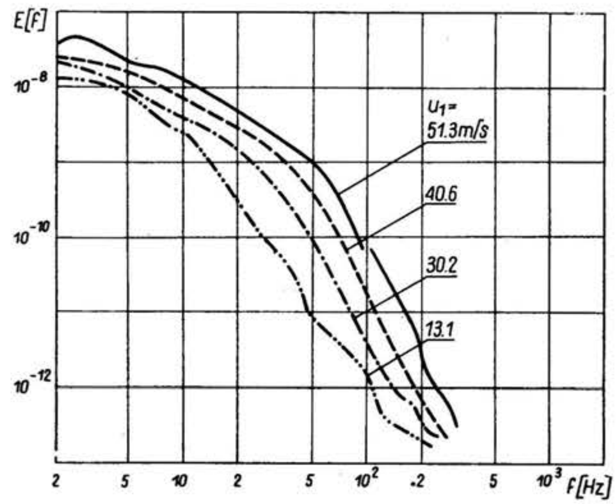


FIG. 13.

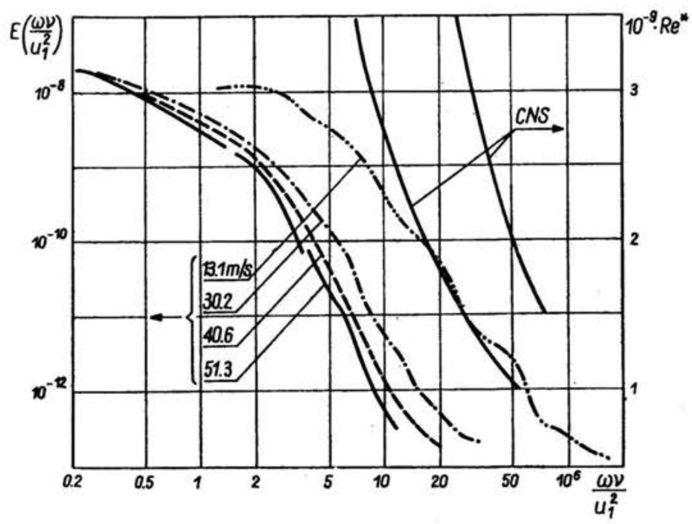


FIG. 14.

frequencies corresponding to instability regions which are more sensitive to the perturbations has a more essential influence on the boundary layer condition. These regions are determined by Re* and the nondimensional frequency $F = (2\pi f\nu)/U_1^2$.

If we compare the free stream turbulence power spectra presented in the usual form $E(f)$ (Fig. 13), we can see that the spectra become more fulfilled both in the amplitude and the frequencies as the velocity increases. However, if we compare the same spectra in the coordinates $E(F)$ (Fig. 14), we can conclude that with a velocity increase the perturbations cover the more and more narrow band of nondimensional frequencies $F = (2\pi f\nu)/u_1^2$ displacing beyond the theoretical instability region (*CNS*). Hence we can explain the transition Reynolds number stabilization in our results by the free-stream turbulence power spectral density displacement beyond the "active" nondimensional frequency region.

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