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EXPERIMENTAL INVESTIGATION OF HIGH-FREQUENCY SECONDARY DISTURBANCES IN A SWEPT-WING BOUNDARY LAYER

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Introduction. The development of spatially localized vortex structures is among the commonly encountered features of the transition to turbulence in wall flows. Flat-plate Λ-shaped vortices, curved-surface Görtler vortices, swept-wing cross-flow instability vortices, etc. may be classified as such structures. In spite of the variety of mechanisms that generate structures of this kind, they are characterized by a high localization in the transverse, and a great length in the longitudinal, direction with respect to a local flow velocity, with their amplitudes reaching 10% of this velocity and over. Their streamwise quasistationariness is a necessary condition for the formation of high-frequency, secondary instabilities [1, 2]. Downstream, the development of the instabilities may lead to complete flow stochasticity. In particular, this favors the transition in the swept-wing flow even for subcritical (with respect to the instability of an undisturbed boundary layer) Reynolds numbers [2–4].

The initial level of flow inhomogeneity plays an important role in the process of development of secondary disturbances [5]. It dictates the amplitude of stationary vortices and their disturbances, which determines their total effect on the transition process. This leads to the fact that the transition to turbulence may proceed in different ways under insufficiently controllable or "natural" experimental conditions, which hinders comparison of results obtained in different works. In particular, Kohama et al. [4] found two different types of disturbances, growing downstream. Either of the two is likely to predominate in the transition process under some conditions or other. However, the relative effect of these disturbances on the transition to turbulence has not been investigated in detail.

The development of several types of instability was also discovered in calculations [6] when the amplitudes of swept-wing stationary vortices exceeded 10% of the local velocity U_0 of the outer stream. In this case their characteristic frequencies and amplification rate factors could differ severalfold. A similar situation is observed on Görtler vortices when there are also a few types of disturbances that determine the transition on each individual pair of vortices [7, 8]. Apparently, the existence of several growing vortex modes is a characteristic feature of a whole class of boundary layer flows that contain stationary or strongly elongated streamwise vortices.

Experimental simulation of such flows under controllable conditions (for instance, the one applied in [9] to the study of a swept-wing secondary instability) provides a possibility of separating these instabilities and studying them individually as well as in interaction with each other, with a mean flow, and with disturbances of other types.

The present work is a direct continuation of [9]. It has been done by the same team of authors. The development dynamics of one type of secondary disturbances and their effect on the transition process under large (up to 30% of the outer flow velocity U_0) amplitudes of stationary vortices were described in [9]. In the present experiments we attempted to simulate the development of another type of traveling waves that are generated on an isolated stationary vortex in a swept-wing boundary layer and to estimate its effect on the transition to turbulence.

The Experimental Procedure as a whole coincides with that described in [9]. The experiments were carried out in a T-324 subsonic low-turbulence wind tunnel at the Institute of Theoretical and Applied

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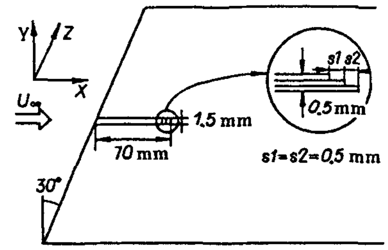

Fig. 1

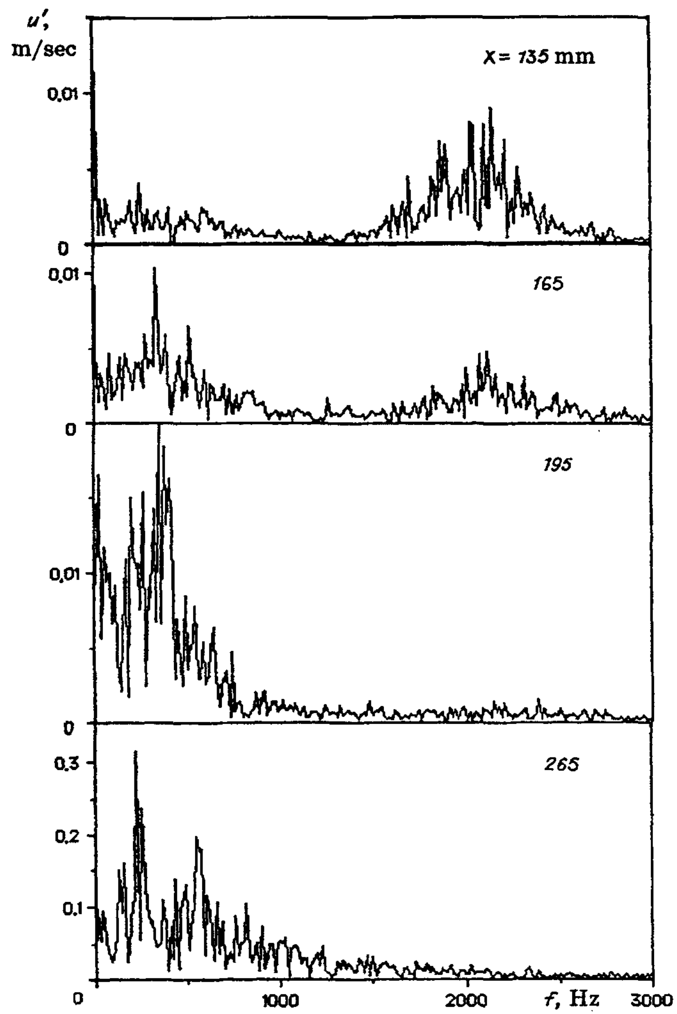

Fig. 2

Mechanics, Siberian Division of the Russian Academy of Sciences. The T-324 closed-type wind tunnel had a closed working unit of length 4 m and square section 1×1 m. The degree of flow turbulence in the test section did not exceed 0.04% of the velocity U_∞ of the approach stream for an experiment velocity of 7 m/sec.

The experiment set-up is presented in Fig. 1. A high-lift wing airfoil of the C-12 type [10] with a sweep angle of 30° and a chord 500 mm long was chosen as a test model. The airfoil consists of a symmetric ogival nose of thickness 16% of the chord and length 5.6 mm, which turns into two identical convergent plane surfaces. The airfoil was placed upright and mounted rigidly to the horizontal walls of the test section so that

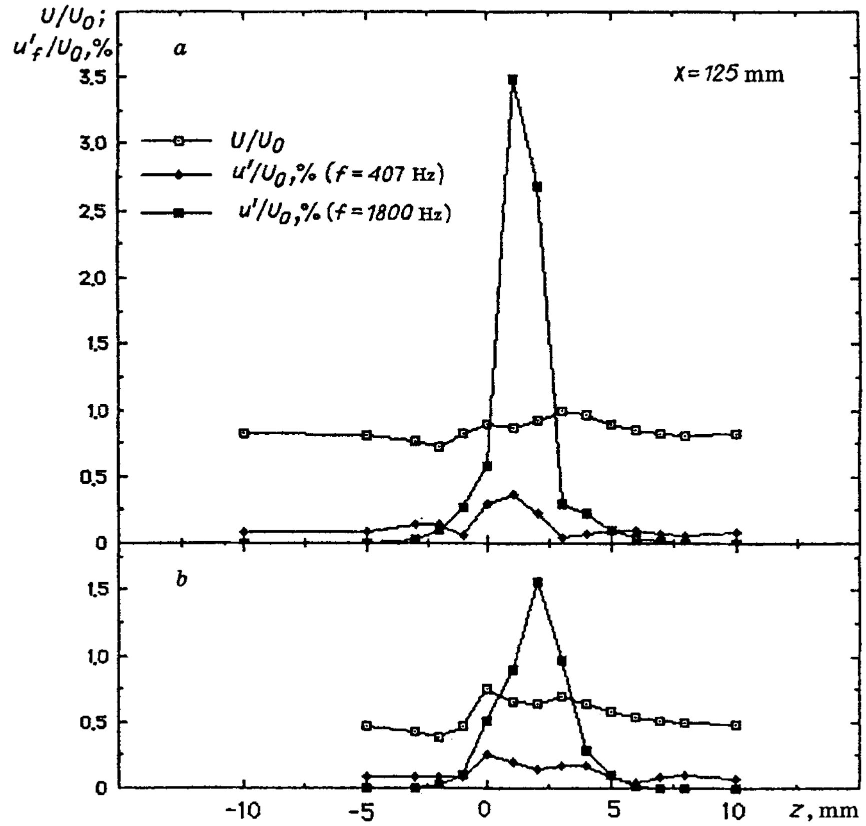

Fig. 3

the test surface of the airfoil represents a flat plate set at zero attack angle.

Stationary disturbances developed behind a ledge, which was glued to the surface. Its shape, size, and location on the wing are shown in Fig. 1. To avoid flow separation, one end of the ledge was extended to the idle side of the wing, while the other was smoothed off.

We used a system of coordinates in which the X axis was parallel to the free stream, the Z axis was directed along the cross-flow current (spanwise), and the Y axis was normal to and reckoned from the wing surface. A traversing device, which kept a sensor in place, was modified in comparison with [9], which made it possible to remove some restrictions on movements in the XZ plane. The device enabled a traversing across the wing surface with an accuracy of 0.5 mm, while normally to the wing ≈ 0.01 mm. The coordinate $Y = 0$ was determined visually with an accuracy of ≈ 0.1 mm and more precisely by linear extrapolation to zero of the unperturbed mean-velocity profiles of the laminar boundary layer.

Most hot-wire measurements were taken in the central part of the model where the secondary flow was practically nonexistent already. A hot-wire anemometer measured only the longitudinal components of the mean and pulsatory velocities U and u'. These signals arrived from the hot-wire anemometer via an analog-to-digital converter at a personal computer where the data were linearized and subject to further processing by a specially developed program in the course of the experiment. Phase detection made it possible to obtain quantitative information on the behavior of controllable waves in a vortex even when their amplitude turned out to be significantly lower than background disturbances.

To excite traveling waves in the wall flow, we applied the procedure [11] for conversion of acoustic oscillations into vortex shear-layer disturbances on a local surface inhomogeneity. The acoustic oscillations

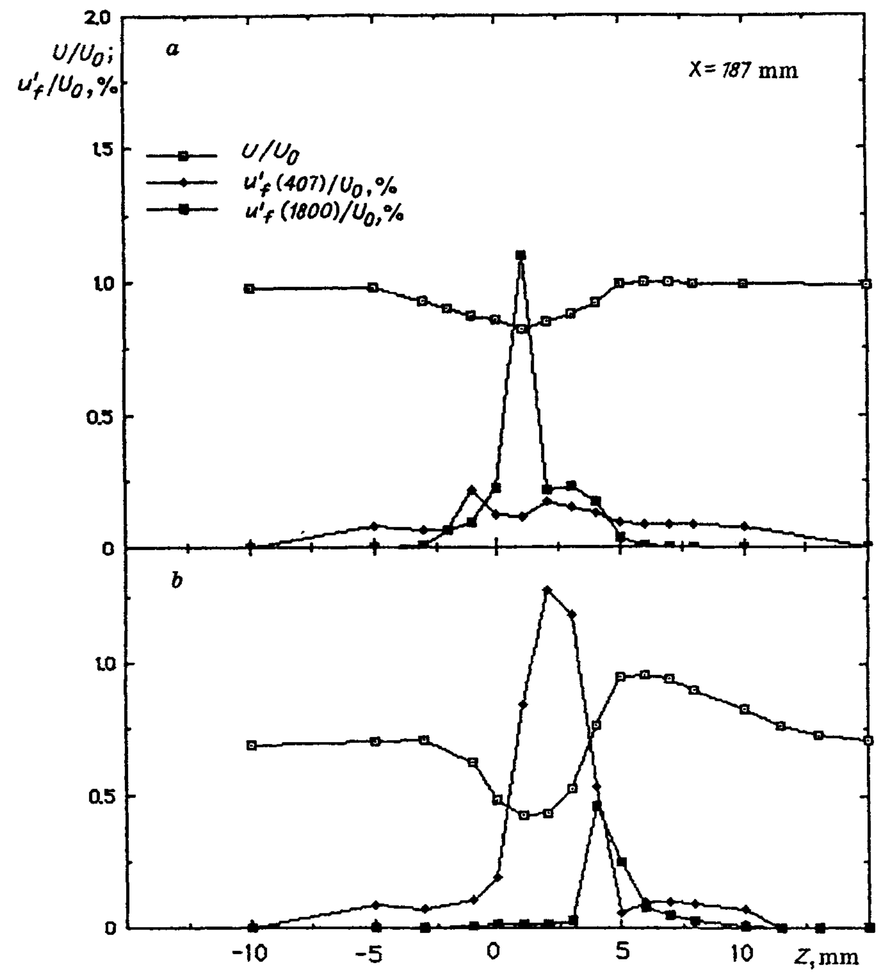

Fig. 4

were generated by two dynamic loudspeakers, which were in the tunnel diffuser behind the model. They emitted the sound in an upstream direction. Audio-frequency generators set the frequencies being applied to the loudspeakers.

The Existence of High-Frequency Disturbances. Spectral measurements showed that several (at least two) packets of disturbances with central frequencies in the vicinity of $f = 400$ and 1800 Hz are formed in the vortex. This is demonstrated by a set of spectrograms in Fig. 2, which were obtained at different positions along X with a fixed Y in the neighborhood of a maximum of integral pulsations inside the vortex. Note that the spectra for $X = 135$, 165, and 195 mm are presented on one scale, and for $X = 265$ mm on another.

It can be seen that whereas the packet with a central frequency close to 1800 Hz stands out in the spectrum at $X = 135$ mm, it decays gradually downstream by $X = 195$ mm, but lower-frequency oscillations with a central frequency about 400 Hz begin to grow even at $X = 165$ mm and fill the spectrum gradually at $X = 265$ mm and downstream. Below, for brevity we will refer to these packets as high-frequency and low-frequency packets, respectively.

The development of the low-frequency packet under controllable conditions was studied in [9]. Recall that here we also applied the same measurement procedure to study characteristics of the high-frequency oscillations and their effect on the development of low-frequency disturbances and the transition to turbulence. The frequencies 1800 and 410 Hz, which were close to the central frequencies of the wave packets, were chosen as seeds.

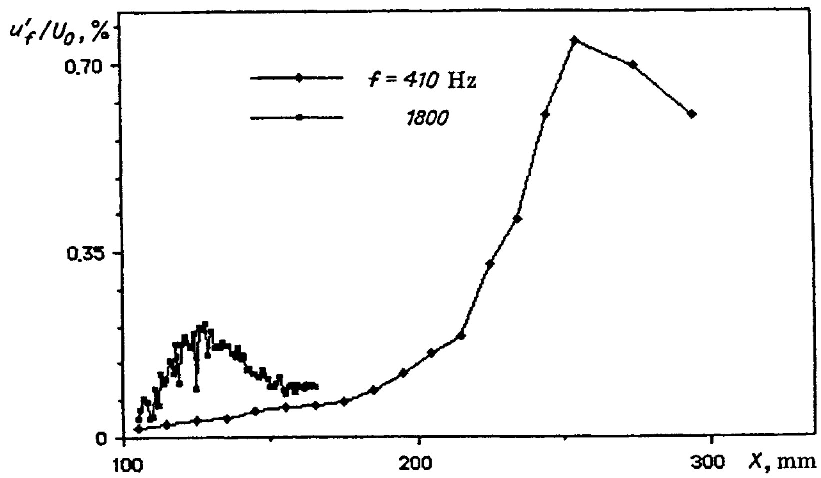

Fig. 5

A maximum of the low-frequency oscillations was observed in [9] in the vicinity of an inflection or a maximum gradient in a transverse mean-velocity distribution. Averaged distributions of the mean velocity $U(Z)$ (the limits of such a representation are discussed in the following section) and the disturbances $u'_f(Z)$ being excited at both frequencies, which were measured in a frequency band of 4 Hz, are presented in Figs. 3 and 4 for $X = 125$ mm and $X = 187$ mm respectively, i.e., at the points along X where both oscillations coexist and are clearly detected. The measurements were carried out at two stations along Y: approximately in the middle (b) and on the outer edge of the boundary layer (a). The velocity distributions $U(Z)$ are normalized to U_0, while $u'_f(Z)$ are expressed as a percentage of U_0. We notice that the disturbances are localized differently both in Z and Y. In particular, the intensity of the high-frequency oscillation is significantly higher in the upper part of the vortex, whereas the low-frequency one is closer to the surface.

At $X = 125$ mm the Z-distribution maximum of the 1800 Hz disturbances is in the neighborhood of a small dip in the velocity distribution $U(Z)$ and runs to 3.5% for a chosen sound intensity. The low-frequency oscillation amplitudes are substantially smaller, and their maximum $u'_f \approx 0.3\%$ is significantly less pronounced. The dip in the mean-velocity distribution disappears gradually by $X = 187$ mm; at the same time the high-frequency wave decays down to $u'_f \approx 1.0\%$, and the low-frequency one builds up to 1.3%. A similar dip was observed in the transverse mean-velocity distribution in [4], where it was ascribed to nonlinear vortex deformation as a result of formation of a vortex crest and its collapse, which led to a secondary influx of low-velocity fluid to the surface.

There is no way to draw definite conclusions regarding the genetic relation between the dip appearance in the mean-velocity distribution and the development of the high-frequency disturbance. In particular, one can suppose that in the upper part of the stationary vortex there exists another highly localized vortex which dissipates downstream. At the same time the results presented in the following section show that the appearance of this dip may be a consequence of the strong effect of natural high-frequency disturbances on the mean flow.

Influence of High-Frequency Disturbances on the Transition. As discussed above, in the natural case initially there may exist at least two wave packets which undergo different evolution downstream. The low-frequency-disturbance amplitude grows, and the spectrum is filled gradually. The high-frequency packet decays gradually and is not implicated directly in the transition.

Figure 5 shows amplification curves for the frequencies under study in the 4 Hz band, which were obtained for a fixed distance from the model surface in the vicinity of the maxima of separately introduced disturbances on frequencies of 410 and 1800 Hz. As in the natural case, the transition occurs via low-frequency-

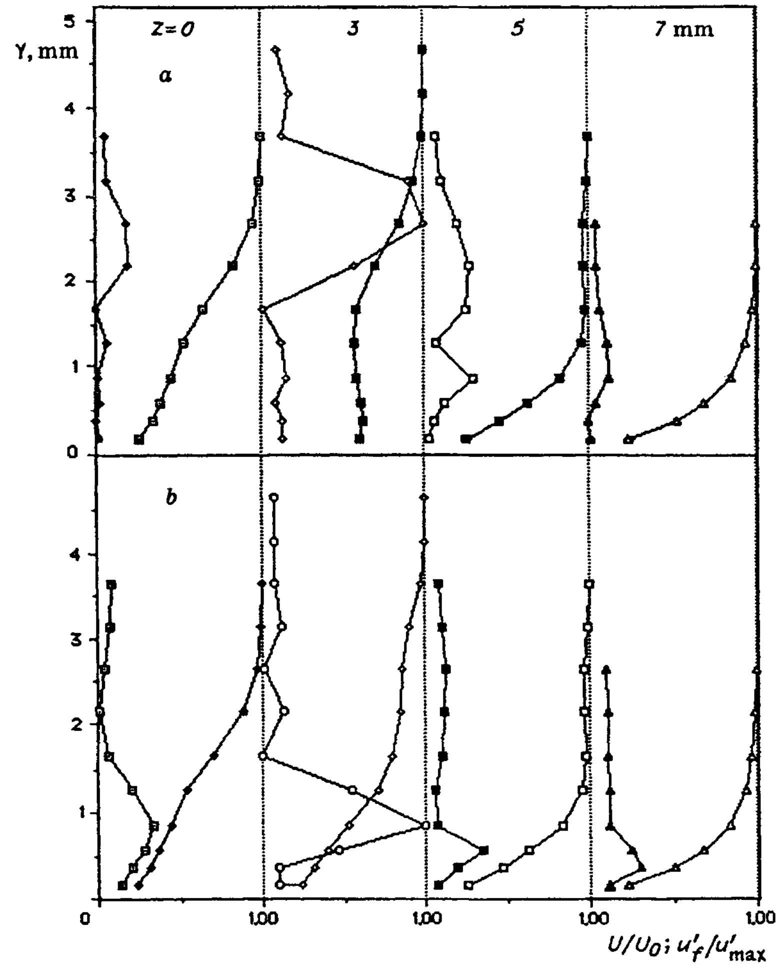

Fig. 6

pulsation growth in an area along X when the high-frequency disturbance is already virtually undetectable and the low-frequency oscillation increments are several times greater than the high-frequency ones. At the same time, the phase velocities of the disturbances on both frequencies turned out to be close to ≈ 0.56 of U_0 in the major part of the wave development region, which is indicative of the possibility of effective nonlinear interaction with energy transfer between the disturbances in the area of their coexistence.

Thereafter most measurements were performed in the range $X = 100$–200 mm, i.e., in the area that covered the high-frequency-wave instability. The intensity of this wave was the same as in Fig. 5.

It is well known that in some cases introduction of new, even small, disturbances can affect the mean flow in the shear layer [12], thus changing the object under investigation itself. Earlier [9], it was discovered for the low-frequency disturbances that the vortex was not deformed noticeably even on introduction of disturbances of amplitude at the maximum of vortex pulsations of about 1% of U_0 at which nonlinear phenomena were usually observable.

As distinct from the low-frequency oscillations, the excitation at the frequency of 1800 Hz affects the flow strongly. Figure 6 presents pulsation profiles $u'_f(Y)$, which were measured for the high- (a) and low-frequency (b) excitations in a band of 4 Hz, and corresponding mean-velocity profiles $U(Y)$. The pulsations are normalized to the maxima $u'_{max} = 1.4\%$ for the high-frequency wave and $u'_{max} = 0.5\%$ for the low-frequency

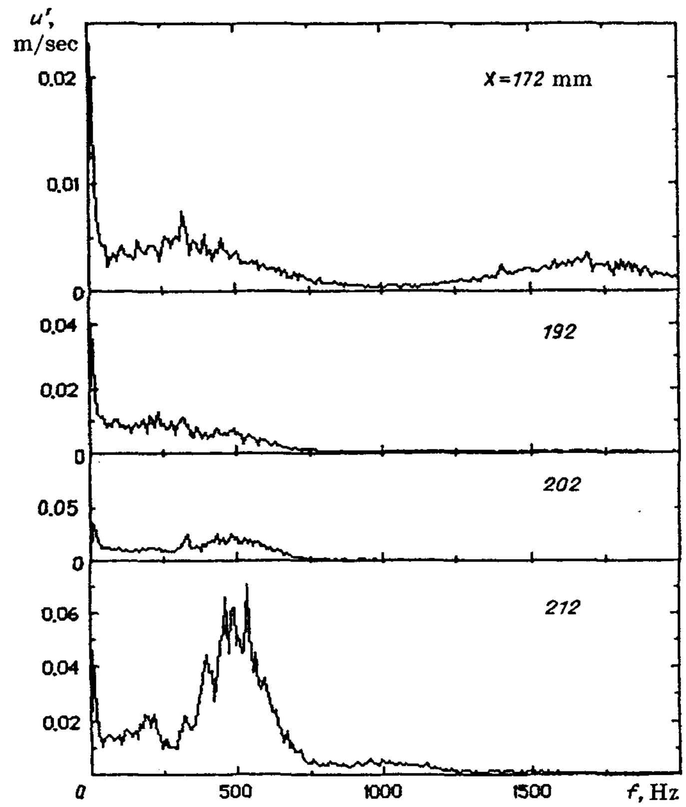

Fig. 7

one, while the mean-velocity profiles are normalized to U_0.

Comparison of Figs. 4 and 6 shows that both disturbances are at a maximum approximately at the same station $Z = 3$ mm. Moreover, in addition to Figs. 3 and 4, these profiles illustrate that the high-frequency disturbance peaks farther from the wing surface than the low-frequency one. It can be seen, however, that the 1800 Hz excitation causes the profile at the station $Z = 3$ mm to change from inflated to inflected. This effect is indistinct at the other stations along Z. In particular, such a localization makes this effect hardly detectable in measurements along Z at a fixed Y (as in Figs. 3 and 4). On the other hand, it should be noted that, being local in Z, this effect exerted on the mean-velocity profiles is not local in the sense that its existence influences the events that take place in an area along X where the high-frequency disturbance has already decayed.

Figures 7 and 8 present sets of the spectra obtained in the natural case and under the high-frequency oscillation excitation respectively. The spectra were taken at the same flow points in the vicinity of a maximum of integral velocity pulsations. In both cases the transition to turbulence proceeds by way of the low-frequency-packet growth, but the disturbances grow and the spectrum is filled earlier in the case of the high-frequency wave excitation. Moreover, a reverse phenomenon, background pulsation suppression, is observed at the first station at $X = 172$ mm. This effect is also observed in other shear flows with prevailing inviscid instability [13]. It is seen from Fig. 5 that the station $X = 172$ mm corresponds to the area of high-frequency wave attenuation. Therefore, the further rapid growth of the low-frequency packet, which is noticeable even at $X = 192$ mm, is more likely to be due to the mean-flow change, against the background of which the low-frequency wave packet develops and causes the transition, than to the direct energy transfer between the disturbances.

Conclusion. Thus, it has been demonstrated that two pulsation packets are formed on the vortex

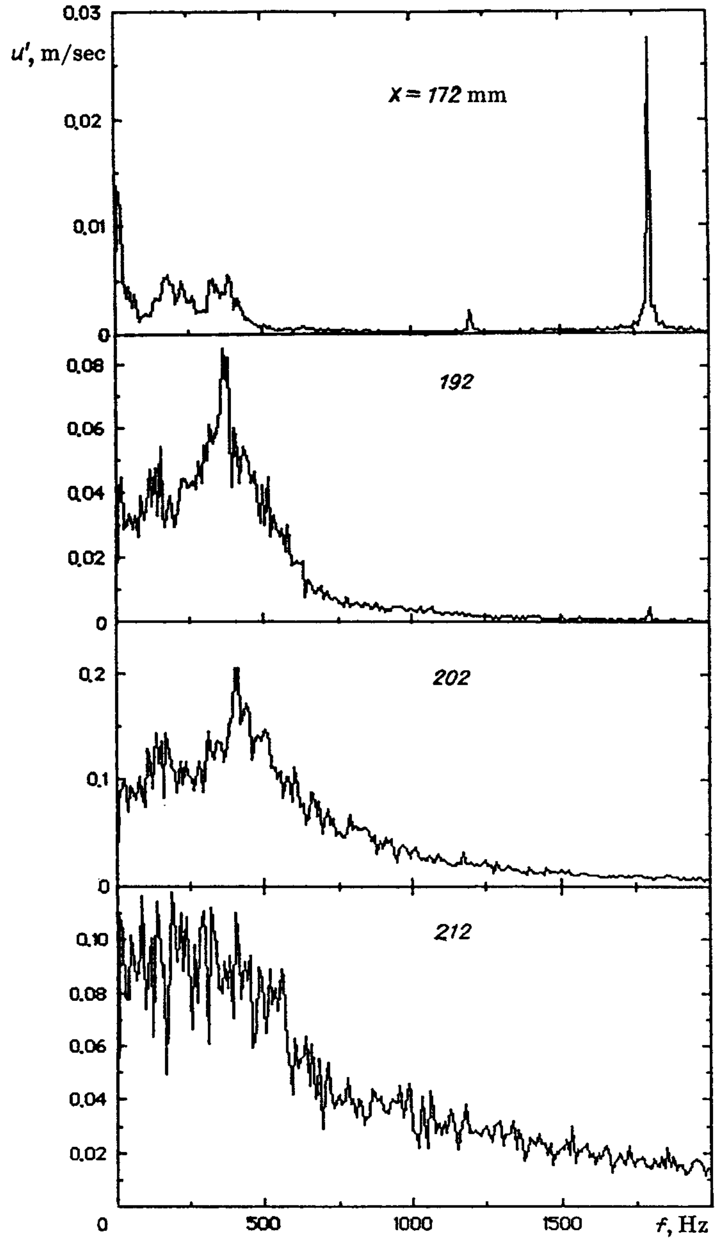

Fig. 8

under investigation, their characteristic frequency ranges and increments differing several times. The packets are localized in the vortex also in different ways. However, the velocities of their propagation along the vortex axis proved to be virtually equal under the conditions in question. As noted above, the early growth of the high-frequency oscillations does not bring about the transition to turbulence by itself; however, their excitation precipitates the transition by changing the mean-velocity profiles, against the background of which the low-frequency instability develops, which is the chief cause of the faster growth of the low-frequency disturbances.

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