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Generation of disturbances by vibrations of localized surface in a flat plate boundary layer

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Abstract
The development of localized disturbances, generated by three-dimensional vibrating surface in the flat plate boundary layer at $Re_{\delta 1}$>600, is experimentally investigated. It is shown, that vibration of a three-dimensional surface with a large amplitude leads simultaneously to the formation of two types of perturbations in the boundary layer: longitudinal localized structures and two wave packets. Spatial development of oscillations at the central frequency of the wave packets is consistent with the linear theory of hydrodynamic stability.

1. Introduction

In the tasks, associated with the drag reduction of flying and swimming devices and calculation of their aerodynamic characteristics, an integrated approach is relevant in the study of all phenomena and factors which can influence on the laminar-turbulent transition process in the boundary layer. One of the investigation methods is a controlled effect on the object, which studies of his reaction or response. Such effects on the boundary layer may be caused by local fluctuation of limited area of the surface. At one of the first experimental study, which examining the excitation of disturbances in the boundary layer of the vibrating surface [1], the simplest case of a two-dimensional vibrator on a flat plate was considered. Comparing with the results of the theory [2], it is shown, that the linear theory of hydrodynamic stability and receptivity for the two-dimensional case correctly describes the development of perturbations in the case of small amplitude vibrations. At the same time, there are interesting cases of sufficiently large vibration amplitudes, when the disturbance in the shear layer cannot be considered linear. Theoretical analysis for such disturbances in the present time is absent. Experimental study of the origin and development of disturbances generated by three-dimensional vibrations of surface in the Blasius boundary layer is presented in [3]. The study shows, that the disturbance forms by the surface oscillations in the boundary layer and it is different from Tollmien - Schlichting waves. Such disturbances were classified as localized streaks [4]. It is well known, that elongated local disturbances play an important role in the laminar-turbulent transition under the high or moderate free stream turbulence level [5].
In addition to longitudinal localized disturbances, a high-frequency, secondary oscillations can exist in the boundary layer. In a number of papers, it is theoretically [6] and experimentally [7, 4] demonstrated the presence, role and possibility of existence of such high-frequency disturbances in the boundary layer on a flat plate at high and moderate level of free stream turbulence. Practically, the longitudinal localized structures (streaks) are damped almost in all experiments under controlled conditions, but the development of high-frequency disturbances or wave packets under certain conditions can lead to the formation of turbulent spots [4]. In [8], the appearance and development of disturbances generated by vibrations of the three-dimensional surface in the straight wing boundary layer was experimentally investigated. It is shown, that vibrations of a three-dimensional surface with a large amplitude lead simultaneously to the formation of two types of perturbations in the boundary layer: longitudinal localized structures and accompanying wave packets. Rapid grow of the wave packets amplitude occurs in the region of unfavorable pressure gradient.
Previous experimental investigations on excitation of disturbances by a localized vibrator in a flat plate boundary layer [3] were carried out at low flow velocities and low Reynolds numbers. Therefore, it is important to study the structure and dynamics of the development of localized disturbances, which is formed by action of low-frequency oscillations of local surface section in the flat plate boundary layer (Blasius) at close to critical Reynolds numbers.

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2. Experimental facility and measurement technique

The investigations were carried out in the T-324 wind tunnel of the Institute of Theoretical and Applied Mechanics SB RAS. Parameters of the test section were 4 m in length and cross section 1 × 1 m. A flat plate was used as an experimental model, which had sizes 1500 × 1000 mm and 10 mm in thickness (figure 1). The plate nose was specifically designed to minimize the effect of the pressure gradient near the leading edge [4]. The plate was installed vertically in the wind tunnel test section at zero angle of attack. The oncoming flow velocity U_∞ was 3.5, 11, 13, 14.7, 16 and 18 m / s. The velocities, which were higher than 11 m/s, provided the $Re_{\delta 1}$> 600 (Reynolds number based on the displacement thickness δ_1) in the investigated region. The turbulence level of the oncoming flow (Tu) was less than 0.04% U_∞. The membrane was located at 150 mm from the plate leading edge and had a rectangular elastic (latex) surface with dimensions 17 × 17 mm, reinforced with a lavsan sticker with dimensions 16 × 16 mm. The membrane was pasted into the model surface in such a way that, in the non-operating state, it adhered to the surface. There was a hole 0.5 mm in diameter under membrane which was connected with hermetic loudspeaker (figure 1). The rectangular shape electrical signal from the generator was provided to the loudspeaker and, as a result, the membrane started movements with a frequency of 2 Hz, from the rest position to the raised position with amplitude of 0.33 mm. Measurements of the flow characteristics were carried out by a constant temperature anemometer with single-probe. The diameter of the probe wire was 5 µm, the length was 1 mm. The longitudinal component of the velocity fluctuation u and the mean velocity U at different points of the measured area (x, y, z) were obtained and fixed. The x-axis with the origin at the plate leading edge was directed along the stream, the z-axis with the origin on the plate symmetry axis was located along the span of the model, the y-axis with the origin on the plate surface was perpendicular to the x, y axes (figure 1). The oncoming flow speed in the wind tunnel test section was measured by a Pitot-Prandtl tube connected to micromanometer. The hot-wire sensor was calibrated in a free stream near the Pitot-Prandtl tube at flow velocities range 1-25 m/s. The error in determining of the oncoming velocity was less than 1%.

Data from the hot-wire anemometer were recorded by means of analog-to-digital converter to the computer's memory synchronously with the start signal for membrane movement from generator. Then, the oscillograms were averaged to improve the signal-to-noise ratio, which made it possible to isolate a useful signal from nondeterministic noises. The averaging was from 5 to 20 individual implementations, depending on the levels of the signal and noise. Further results processing was carried out on a computer using a space-time Fourier transform. Signal filtering with allocation of its high-frequency component was carried out by means of direct and inverse Fourier transform in a chosen frequency range. The direct Fourier transform of the hot-wire signal gave information of its spectral composition, and then the frequency range containing the disturbance (wave packet) was chosen, with all other frequencies faded. The inverse Fourier transform for the modified frequency spectrum was performed, which reconstructed the signal in the amplitude-time coordinates.

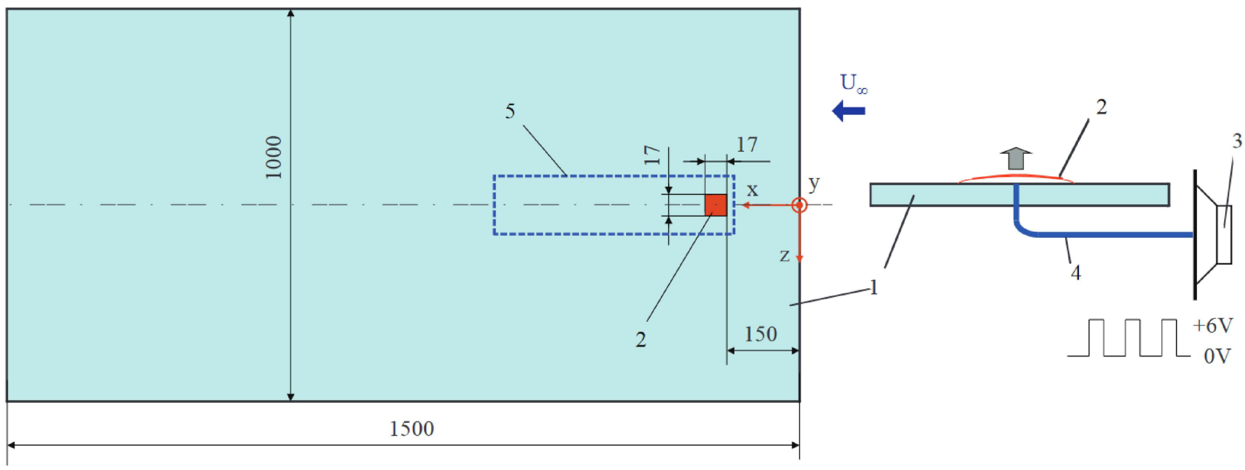

Figure 1: Set-up, dimensions in mm; 1–plate, 2–membrane, 3–loudspeaker, 4–pipeline, 5–measurement area.

3. Results

Mean velocity measurements within the boundary layer (figure 2) showed that the Blasius flow was realized in the investigated region of the boundary layer. In figure 2, the solid line showed the theoretical solution of Blasius, and the experimental points, which measured in the present experiment for U_∞ = 16 m/s. The results showed that the

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mean velocity profile of the undisturbed flow was close enough to the Blasius theoretical solution. The shape factor was H=2.599 ($H=\delta_1 / \delta_2$) at x = 200 mm.

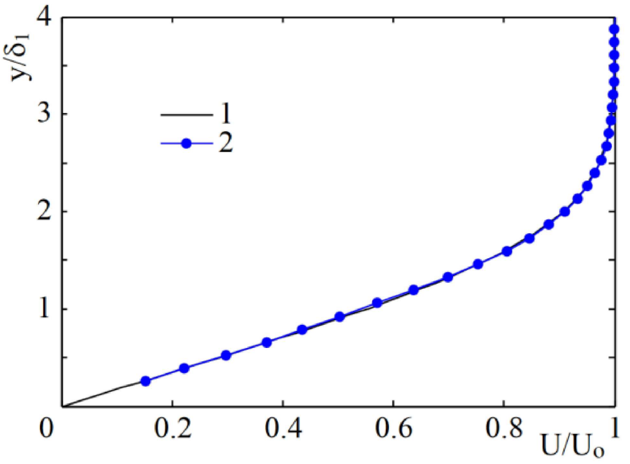

Figure 2: Mean velocity profiles of theoretical Blasius (1) and measured base flow (2), U_∞ = 16 m/s, x=200 mm.

The contour lines of equal velocity fluctuations, plotted in the z-t and y-t plane for the oncoming velocity U_∞ = 16 m/s behind the membrane, are shown in figure 3 and 4. Impulse action of the membrane on the boundary layer led to the formation of localized disturbances downstream. From the distribution of velocity fluctuations along the transverse coordinate at z-t plane figure 3 (a), it is seen that near z = 0 there was the velocity defect area (denoted by blue lines), generated by the deviations of the membrane upwards. It can be explained by the fact that the boundary layer flow with low-velocity pushed out by the membrane falls into the measured region. On each side of the defect zone, the formation of two distinct regions with excess velocity (red solid lines) was located opposite the side boundaries of the membrane (z=±8.5 mm). Further, at z>±11 mm, an additional regions of the velocity defect were formed, which decayed along a transverse coordinate to an unperturbed state (z>±15 mm). These pictures are typical for the so-called longitudinal localized perturbations, or streaky structures, "puff" structures, which were described in detail in [4].

The distribution of velocity fluctuations along the normal to the surface direction at z = 0 is shown on figure 4 (a). It can be seen that the longitudinal disturbance (velocity defect) was located inside the boundary layer. The duration of the longitudinal localized disturbances, generated by the membrane, corresponded to the time when the membrane was located in the raised position, was equal to 200 ms. As shown in [8], in addition to longitudinal localized structures, the membrane was capable to generate the wave packets near the leading and trailing fronts of longitudinal structures, i.e. at moments, when membrane was moving.

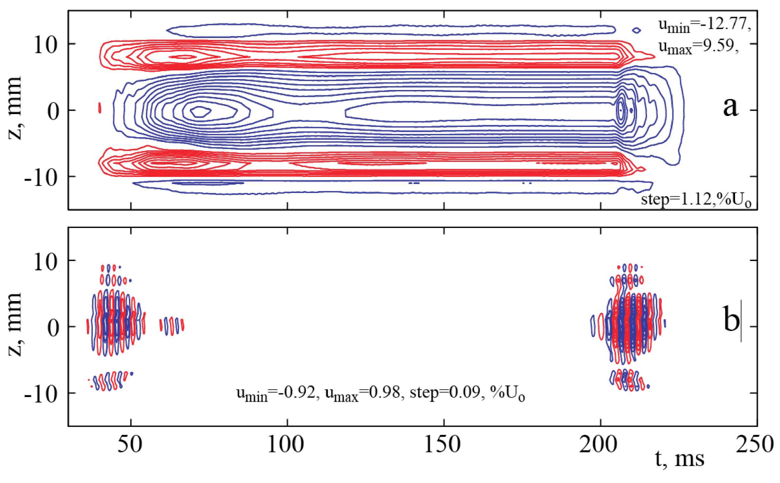

Figure 3: Contours of velocity fluctuations in z-t plane at y=0.8 mm (u_{max}), x=200 mm,
(a) – not filtered; (b) – filtered in a frequency band 200-350Hz

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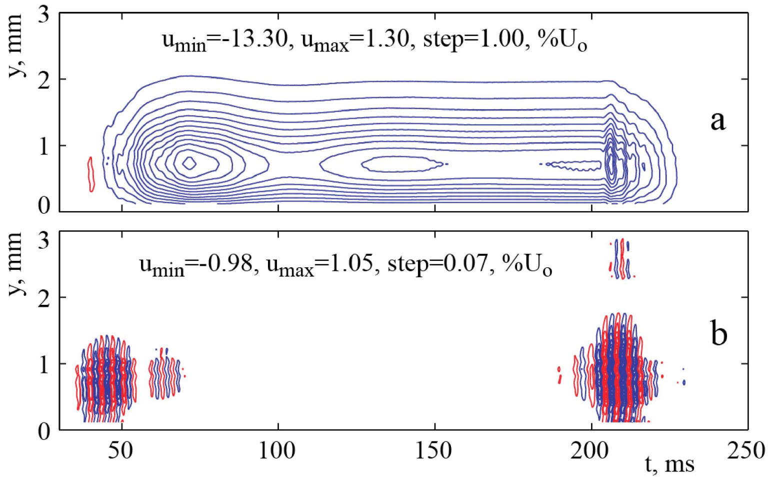

Figure 4: Contours of velocity fluctuations in y-t plane at z=0 mm, x=200 mm,
(a) – not filtered; (b) – filtered in a frequency band 200-350Hz

In order to extract these low amplitude wave packets from the initial signal, a filtration procedure was used. The essence of filtration method is set out in the previous section of the experimental procedure. The results of filtration are shown in figure 3 (b) and 4 (b), while the frequency range 200<f<350 Hz corresponding to the observed wave packet was considered. It can be seen that the wave packets were concentrated in the regions where (when) the membrane moved. Near the leading front (t = 30 ms), when membrane moved from the surface to deflected position, and the rear one (t = 220 ms), where the membrane moved downward. Between these fronts, as was shown above, there was a longitudinal localized structure, which was in fact, a local distortion of the average flow velocity.

The RMS distribution of the wave packets at the leading and trailing fronts along the normal to the surface direction (y) for the velocity U_∞ = 16 m/s is shown on figure 5. It can be seen from the figure, that the velocity fluctuations profile containes two maxima, one near the wall (at y = 0.5 mm) and the second near the border of the boundary layer (y = 3.5 mm), which is typical for the Tollmin-Schlichting wave packets. The amplitudes of the wave packets differ significantly: the amplitude of the wave packet on the trailing front is 2 times greater than in the leading one. This result is also visible from figure 4 (b).

Let turn to analyze of the results, which showing the evolution of generated by the membrane disturbances downstream along the flat plate. The distribution of the longitudinal localized structure intensity downstream the boundary layer flow is shown on figure 6. It can be seen that the amplitude of the longitudinal structure monotonically decreases from x = 300 to 600 mm. This value decays from 17% to 7% U_∞. The fact of damping of longitudinal structures was noted earlier in [9-12] both for the flow on a flat plate and for the gradient flow over a wing profile.

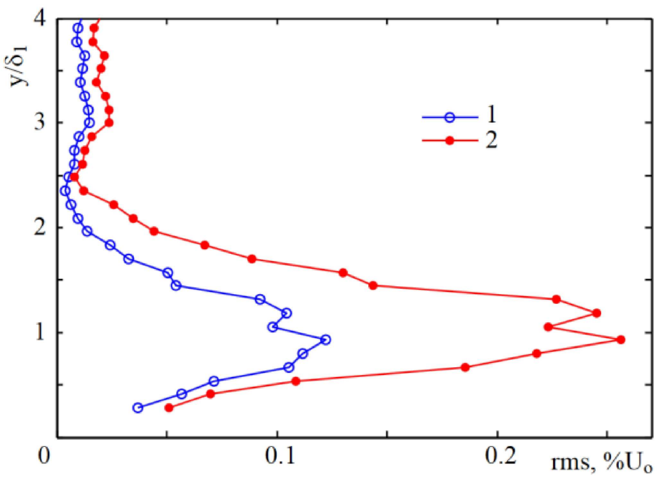

Figure 5: RMS of velocity fluctuations near leading (1) and trailing front (2)

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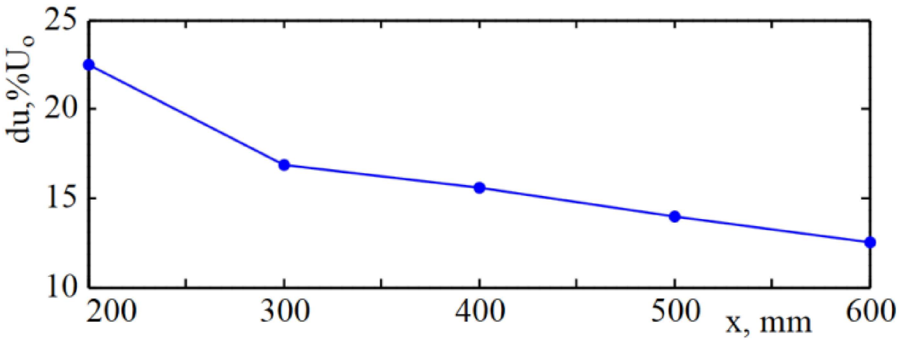

Figure 6: Distribution of the localized streak amplitude downstream at U_∞=16 m/s, $y=y_{umax}$

Figure 7 (a) and (b) shows the distribution of the amplitude of wave packets along the x axis at the leading and trailing fronts for free stream velocities U_∞=16 and 18 m/s. At U_∞=16 m/s, figure 7 (a), the amplitude of the wave packet on the leading front decays in the region from x = 200 mm to 500 mm and then has a small increase at x = 550 mm. The wave packet on the trailing front, on the contrary, increases up to x = 450 mm and then its amplitude passing maximum slightly decays, that indicates the formation of a turbulent spot. Wave packets at U_∞ = 18 m/s, figure 7 (b), both on the leading and on the trailing front tend to grow rapidly from the beginning of the measurement area.

As noted in paper [8], the rapid growth of wave packets is observed in the flow region with adverse pressure gradient, or in separation area. In our case we obtained analogous results for the Blasius flow, i.e. increasing of the wave packets, which formed near the front of the longitudinal localized structure. Since the boundary layer flow in this experiment is close to the Blasius flow, we can use a well-known solution for the stability of the Blasius boundary layer to analyze the obtained results. To do this, we need to determine the wave packet frequency. The time trace and its power spectra is shown on figure 8 for the U_∞=16 m/s at the maximum position in y coordinate. The power spectrum indicates 3 peaks. The second peak at f≈280 Hz corresponds to the wave packets near leading and trailing front of the localized streak (1 and 2 accordingly). It should be noted, that the frequencies only in a range $20<f<800$Hz at the power spectrum are presented. By the same manner we found wave packets frequencies for all tested cases in present experiment. A neutral stability curve for the Blasius flow, calculated from a nonparallel theory is plotted on figure 9. The solid line represents a theoretical solution that separates the regions of stable and unstable flow [4]. The calculated parameters of the wave packets, observed in the experiment, were plotted on this plane (for U_∞=3.5, 11, 13, 14.7, 16 and 18 m/s). Wave packet amplitude grows, if its frequency belongs to the unstable region (U_∞=13–18 m/s), and decays if it is out of this range (U_∞=3.5 and 11 m/s).

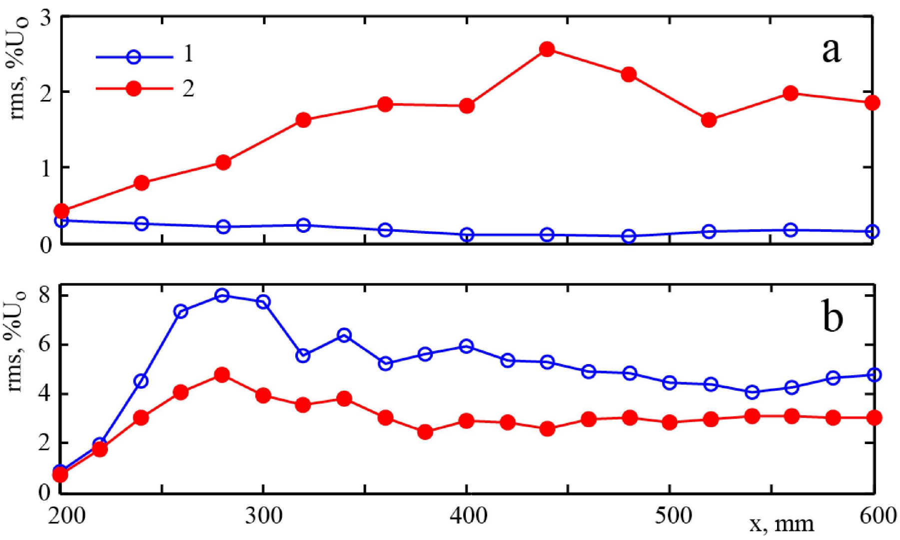

Figure 7: Distribution of the wave packets amplitude downstream, at leading (1) and trailing (2) front, z=0 mm $y=y_{umax}$; (a) – for the U_0=16 m/s, (b) – U_0=18 m/s.

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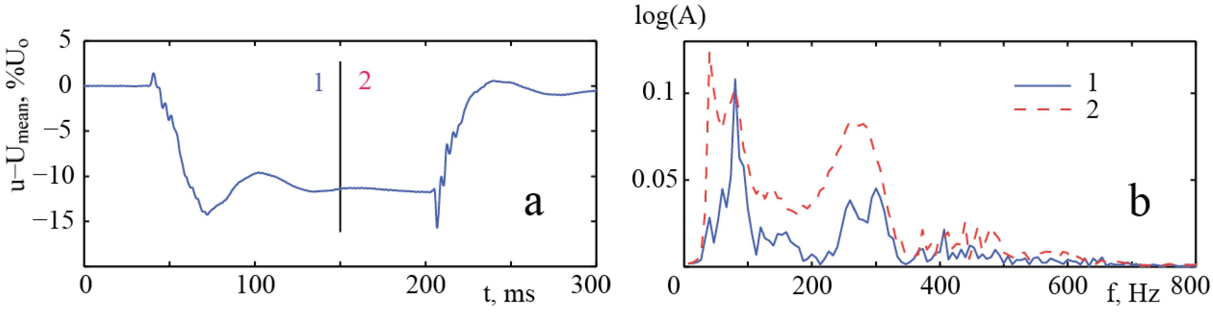

Figure 8: Time trace (a) and its power spectrum (b) at leading (1) and trailing (2) front; $z=0$ mm $y=y_{umax}$; $x=200$ mm, $U_\infty=16$ m/s

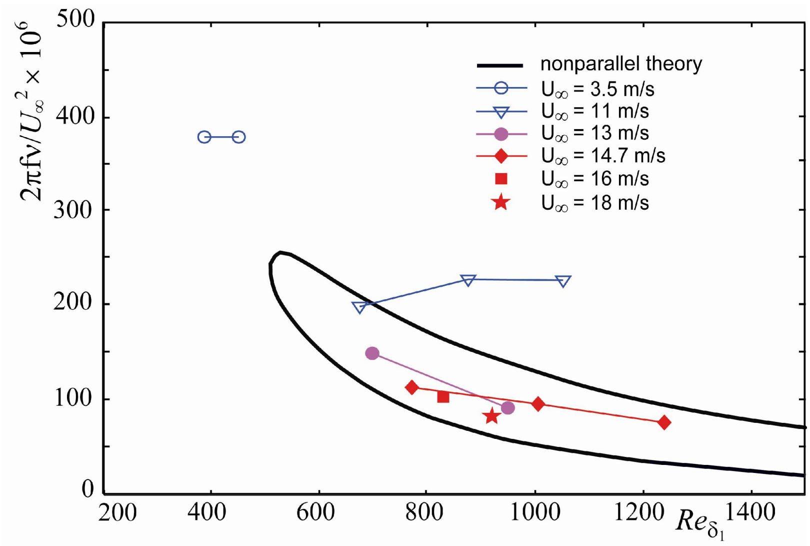

Figure 9: Neutral stability curve

3. Conclusions

It was observed that the pulsed vibrations of the membrane in the Blasius boundary layer leads to formation of longitudinal localized structures and wave packets.

It is shown that the amplitude of the longitudinal structure decreases downstream in the investigated oncoming velocity range. Analysis of the downstream distribution of wave packets amplitude shows that its intensity grows at the oncoming flow velocity range of $13< U_\infty<18$ m/s and decreases at $U_\infty= 3.5$ and 11 m/s.

Spatial development of oscillations at the central frequency of the wave packets is consistent with the linear theory of hydrodynamic stability.

Acknowledgments

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