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Evolution of perturbations of laminar flow behind the ledge of the surface generated by its localized vibration

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Abstract
The origin and evolution of perturbations generated by low frequency localized local vibrations of the wall at flow separation behind a backward-facing step on a flat plate is investigated in a subsonic wind tunnel. The results are obtained using the hot-wire anemometry technique. It is found, that the wall vibrations produce disturbances of the separation region named streaky structures accompanied by wave packets of oscillations. Laminar boundary layer separation induces the growth of wave packet followed by near-wall flow turbulization.

Introduction

Presently, an interest of the researchers of transition to turbulence in boundary layers has been attracted by localized laminar flow disturbances referred to as "streaky structures". The formation of these structures is a result of the nonmodal growth of hydrodynamic disturbances, which is beyond the framework of the conventional model of shear-layer instability with respect to elementary waves [1–3]. The experimentally observed streaky structures are quasisteady deformations of a shear layer, oriented streamwise and localized in the transverse direction. Generated in the boundary layer due to different factors, for example, the external flow turbulence, they favor the amplification of wavy disturbances followed by transition to the turbulent flow regime.
The recently detected instability effect associated with the streaky structure formation consists in the generation of Tollmien–Schlichting wave packets on their fronts. The packet generation and evolution was investigated in detail in the earlier experimental studies of the present authors in modeling the streaky structures in the boundary layer using different techniques. They included the structure generation by air injection/suction through slots in the body surface, its localized vibrations, and by vortical disturbances of the oncoming flow both in gradient and gradientless flows [4–10].
The present investigation of the development of localized shear-layer disturbances in conditions of boundary-layer separation is undertaken as the continuation of the above-mentioned experiments. Usually, laminar flow separation is accompanied by its destabilization, that is, a comparatively fast growth of the vorticity disturbances in the separated boundary layer followed by transition to turbulence. In the classical linear stability theory of quasiparallel shear flows this is attributed to the formation in the separation zone of mean velocity profiles with an inflection point, which are more unstable against small-amplitude oscillations than the local velocity distributions in the attached boundary layer (see monograph [11] and the original studies [12–14]). The theoretical inferences are in agreement with the results of experimental studies and the data of direct numerical simulation in local separation regions, including those past two-dimensional surface imperfections; the references to numerous publications concerning this subject can be found in [15].
Thus, one expects that the development of the wave packets generated by spatially localized low-frequency disturbances of the near-wall flow is considerably influenced by laminar boundary layer separation. In the present study, this possibility is checked under the conditions of separated flow over a rectangular backward-facing step on the surface of a flat plate placed parallel to a low-velocity air flow.

Experimental setup

The experiments were conducted in the low-turbulent T-324 wind tunnel of the Khristianovich Institute of Theoretical and Applied Mechanics of the Siberian Division of the Russian Academy of Sciences (Novosibirsk). This is a closed-

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circuit wind tunnel with a closed square 4 m-long test section measuring 1×1 m. In the test section the freestream turbulence level is less than 0.04%. The tunnel is designed for experiments at low subsonic flow velocities up to about 50 m/s.

A flat plate, 1500 mm in length, 1000 mm in width, and 10 mm in thickness, was used as the experimental model mounted vertically in the test section at zero incidence; its nose was designed in the shape of two conjugate semi-ellipses (Figure 1). On the working side of the plate there was a coverplate measuring 99×300 mm, whose rear section formed a rectangular backward-facing step on the surface, h = 3.0 mm in height, at a distance of 144 mm from the leading edge of the model. The low-frequency disturbance of the laminar flow was generated by controlled oscillations of an elastic dacron square membrane with a side of 17 mm mounted on the plate surface near the step in the central section of the model. The membrane was set into motion by a dynamic loudspeaker, whose movable diffuser was tightly connected with it by means of a pneumatic system. Rectangular electric pulses, 2 Hz in frequency, 0.2 s in duration, and 6 W in amplitude, were supplied on the speaker. When a pulse was supplied, the speaker diffuser was set into motion and produced an excess pressure in the pneumatic system deflecting the membrane from the wall, whereupon it returned into the original position. The pulse generation was synchronized with the signal recording by the measuring equipment. The fixed maximum membrane deflection normal to the surface was 0.33 mm.

The measurements were performed using a one-wire probe and a A.A. Lab. Systems Ltd constant temperature anemometer of model AN1003. The probe was displaced in the measurement region using a programmed traversing mechanism with an accuracy of 0.02 mm in the longitudinal and transverse directions and 0.005 mm normal to the model surface. The time-average U and fluctuating u components of the longitudinal flow velocity were measured.

The Prandtl tube combined with a liquid micromanometer measured the flow velocity in the test section of the wind tunnel. The hot-wire probe was calibrated in the oncoming flow in the velocity range from 1 to 15 m/s; the error in determining the mean flow velocity was smaller than 1%.

The original experimental data were a set of oscillograms recorded at different measurement points near the model surface. The hot-wire signal digitized by the NI-6023 16-bit analog-to-digital converter was acquired in the memory

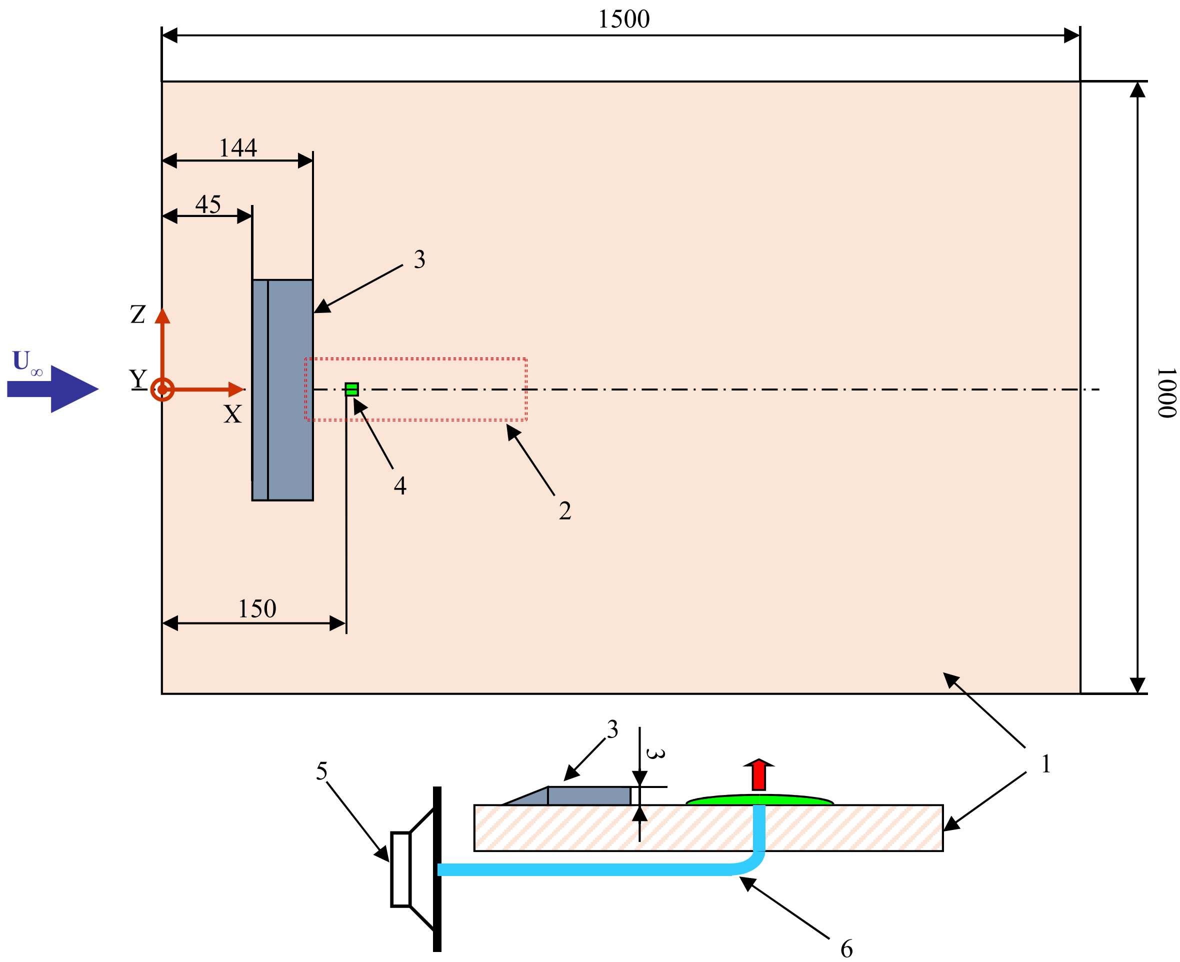

Figure 1: Schematics of the experiment; *1*- plate; *2*- area of measurements; *3*- coverplate; *4*- membrane; *5*- dynamic loudspeaker; *6*- pneumatic system; dimensions are in millimeters.

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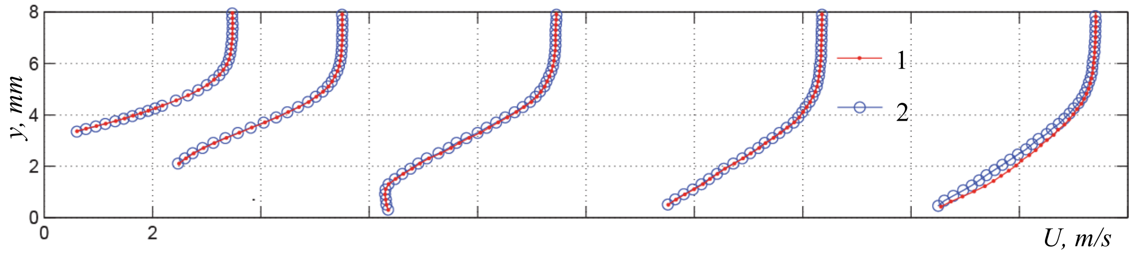

Figure 2: Mean velocity profiles of the flow measured in the z = 0 section and to x = 140, 160, 200, 250, and 300 mm from left to right. 1- disturbed flow, 2- undisturbed flow.

of a personal computer with the ensemble-averaging of the oscillograms to improve the signal/noise ratio. The averaging was performed using 5 to 20 realizations, depending on the levels of the picked-out signal and the noise.
The measurement data processing and the signal filtration (isolation of its high-frequency component) were performed successively applying the direct and inverse Fourier transforms to on the chosen frequency range. The direct Fourier transform of the hot-wire signal oscillograms gave an idea of its spectral composition. Then the frequency range corresponding to the disturbances under study, that is, the wave packet, was selected, while the other spectral components were neglected. The frequency spectrum thus modified was exposed to the inverse Fourier transform with the signal restoration in the amplitude-time coordinates.
The experimental data are obtained at the oncoming flow velocity U_∞ = 3.5 m/s and the corresponding Reynolds number Reh = $U_\infty h/\nu$ =670. The origin of the adopted coordinate system is on the leading edge of the plate, in the plane of symmetry of the model, the x axis is aligned with the flow, the z axis is directed along the leading edge, and the y axis is perpendicular to the x and z directions, with the origin at the plate surface.

Results of the investigation

The time-average basic flow in the vicinity of the backward-facing step is presented in Figure 2. In the leftmost section x = 140 mm the velocity profile of the separating laminar boundary layer is shown; the displacement and momentum thicknesses of the layer are 1.16 and 0.46 mm. At x = 160 mm the velocity distribution is measured above the membrane, near the separation line, while the other profiles are measured further downstream from the step. In the x = 200 mm section the U(y) profile takes the shape characteristic of separated flows; at x = 250 and 300 mm the flow is reattached to the plate surface.
According to [4], the pulses of membrane generate in the boundary layer the disturbances of two types, namely, a streaky structure localized in the direction transverse to the flow and wave packets of oscillations near its forward and rear fronts. By way of illustration, the disturbance generated in the separation zone is presented in Figure 3 by the contours of the positive (red) and negative (blue) deflections of the longitudinal velocity component from its undisturbed value measured when the oscillation generator is turned off. At 200 ms duration of the membrane-induced separated-flow disturbance the transverse dimension of the streaky structure correlates with the membrane width on the interval Δt = 160 to 220 ms. Near the forward and rear fronts of the streaky structure the wave packets of oscillations are formed on the intervals Δt = 50–150 and 220–300 ms. Further on, in processing the results of the analogous measurements the amplitude characteristics of the fluctuations were determined separately in three disturbed flow regions, namely, in the central region of a streaky structure (where the contribution of the high frequency oscillations into the velocity fluctuations is negligibly small) and in the regions of the wave packet development in the vicinities of the leading and rear fronts of the streaky structure.

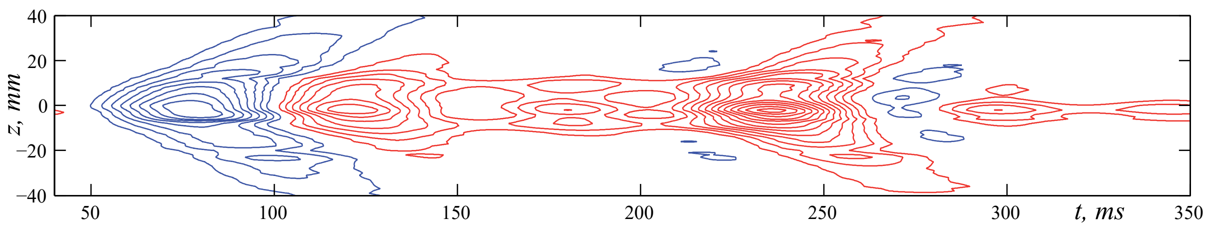

Figure 3: Velocity disturbance contours in the (z, t) plane at a the maximum of perturbations over the y coordinate at x = 200 mm. Frequency band 2-20 Hz. Red lines and blue lines are the positive and negative deviations of the longitudinal velocity component from its undisturbed value. Maximum negative and positive velocity deviations are −4.44 and 6.75%, respectively; the step of the contours is 0.5%U_∞.

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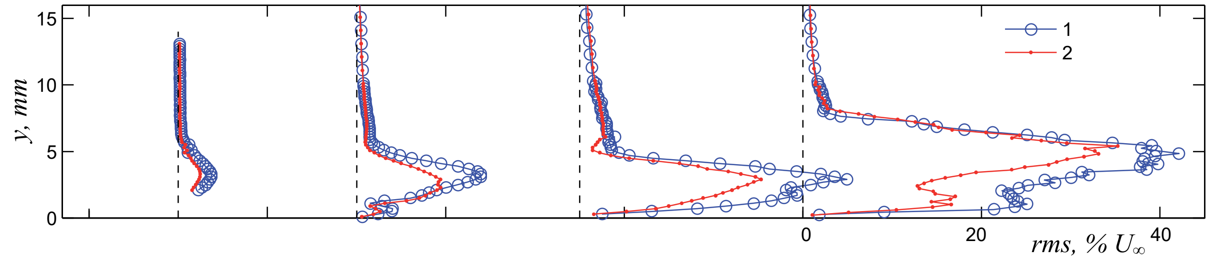

Figure 4: R.m.s. disturbance amplitude profiles. The frequency band is 2-5000 Hz in the z = 0 section and x = 160, 200, 250, and 300 mm; 1- the wave packets on the leading front of the streak, 2- the wave packet on the rear front of the streak.

The flow velocity gradients induced by the streaky structure stimulate the amplification of high frequency oscillations, as shown in Figure 4. Due to the difference of velocity gradients in the vicinities of the leading and rear fronts of a streaky structure, the associated oscillations have different amplitudes, being more intense on the leading front.

The spatio-temporal structure of the disturbances induced by the membrane oscillations is presented in Figures 5 and 6 by the contours of the longitudinal velocity deviation from its undisturbed value in the (y, t) and (z, t) coordinates. The wave packet near the leading front which is observed in the 50 < t < 150 ms range arises, when the membrane moves away from the model surface. Then the membrane remains in a fixed position, whereupon it returns toward the plate generating the wave packet on the rear front on the 220 < t < 300 ms interval. We note the more "ordered" periodic-in-time wave packet structure on the leading front of the low-frequency disturbance. A maximum fluctuation level at the middle of the separated shear layer near y = 3 mm is characteristic of the amplitude distribution of the instability waves growing in a flow with laminar boundary layer separation.

The disturbance oscillograms recorded at different distances from the step at the position of perturbation maximum over the coordinate y and the corresponding amplitude oscillation spectra are presented in Figure 7. The spectral distributions for the wave packets on the leading front of streaky structure were calculated from the oscillograms on

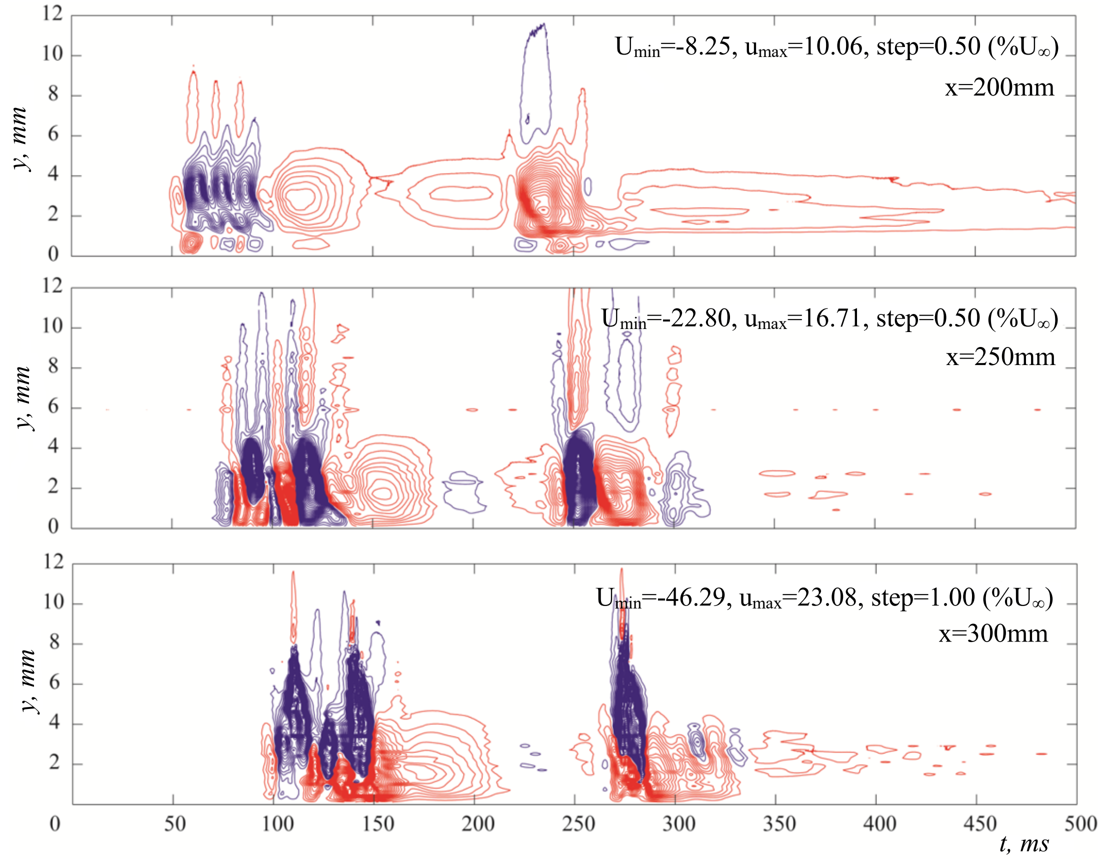

Figure 5: Contours of velocity disturbance in the (y, t) plane at z = 0 and x = 200, 250 and 300 mm on the time intervals 0–500 (a). Maximum negative and positive velocity deviations are 8.25 and 10.06%; -22.80 and 16.71; -46.29 and 23.08, respectively; the step of the contours is 0.5-1% U_∞.

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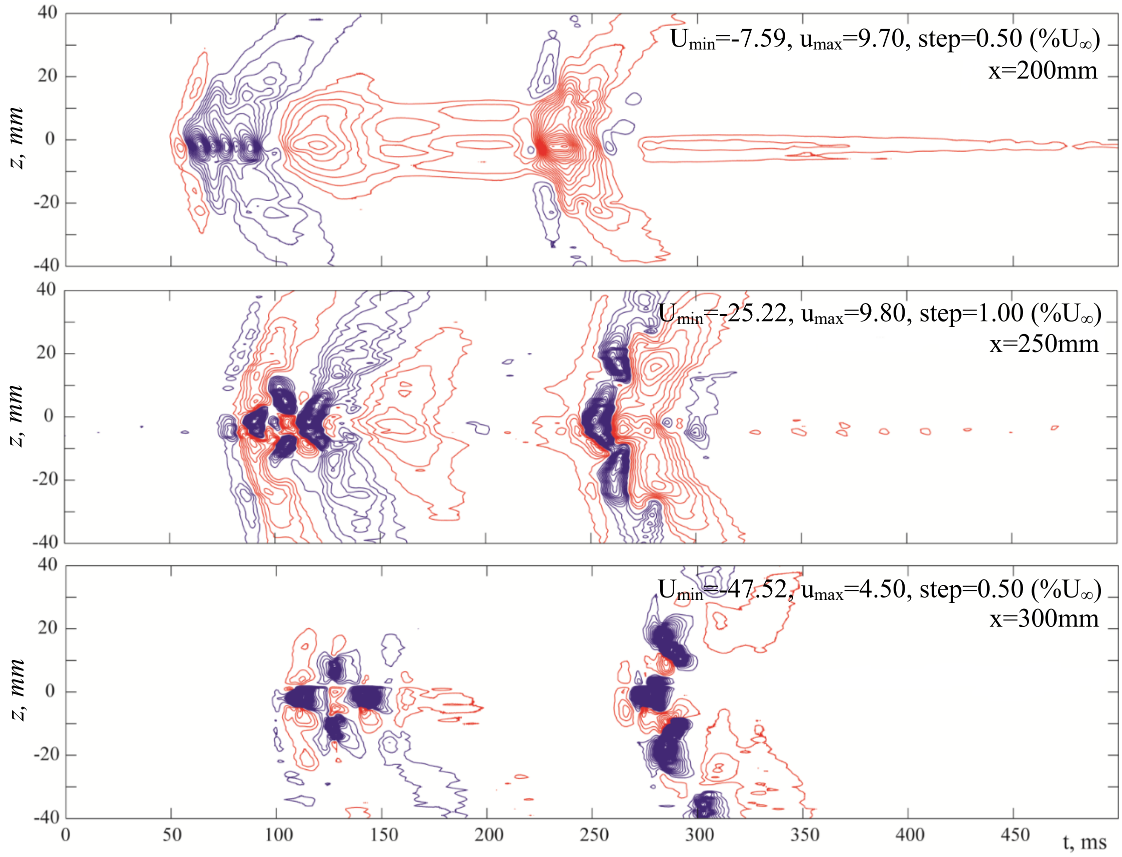

Figure 6: Contours of velocity disturbance in the (z, t) plane at the maximum of perturbations over the y coordinate and at x = 200, 250 and 300 mm on the time intervals 0–500. Maximum negative and positive velocity deviations are -7.59% and 9.70%; -25.22 and 9.80; -47.52 and 4.50, respectively; the step of the contours is 0.5-1%U_∞.

the time intervals 50–150, 60–180, and 90–200 ms at x = 200, 250, and 300 m, while those on the rear front were determined at the corresponding x coordinates and the time intervals 220–300, 230–340, and 250–350 ms.

In the first section x = 200 mm three maxima at the frequencies of about 40 and 75 Hz, together with low-frequency oscillations near f = 0, predominate in the oscillation spectra on the leading front (Figure 7b, curve 1). The possible explanation of the spectral distribution follows from the correlation between the properties of the linear stability of separated flows and the integral characteristics of their local velocity profiles. In [16] in generalizing the experimental results for separation regions under different geometric conditions an empirical correlation between the frequency of the most growing oscillations and the displacement and momentum thicknesses of the separated velocity profile and the external-flow velocity was proposed. For the velocity distribution measured at x=200 mm the correlation dependence estimates the oscillation frequency as about 65 Hz. Thus, the spectral peak which is found near 75 Hz apparently corresponds to the central frequency of the instability wave packet, while the disturbances at f ≈ 40 Hz correspond to its subharmonic components. The amplitudes of these spectral components considerably increase further downstream, in the sections x = 250 and 300 mm.

The spectrum of the wave packet at the rear front of the streaky structure in the x = 200 mm section is qualitatively different (Figure 7b, curve 2). In this case, two oscillation maxima are distinguished at the frequencies of 10 and 84 Hz, they vanish with increasing distance from the step with the formation of a monotonic spectral distribution in the range from 0 to 120 Hz. In the last section x = 300 mm (Figure 7f) oscillations an the higher frequencies, from 150 to 200 Hz, stand out on the leading and rear fronts; they are associated with the turbulent spot generation in the reattached boundary layer.

The downstream variation of the level of disturbances induced in the separation region by the membrane oscillations is shown in Figures 8 and 9. The intensity of quasi- stationary streaky structures increases approximately twice in the upstream part of the separation zone, while decreasing in the regions of boundary layer reattachment and transition to the turbulent flow regime (Figure 8).

The boundary layer separation has a much more pronounced effect on the evolution of high-frequency wavy disturbances. The dependence of the r.m.s. oscillation amplitude on the longitudinal coordinate is presented in Figure

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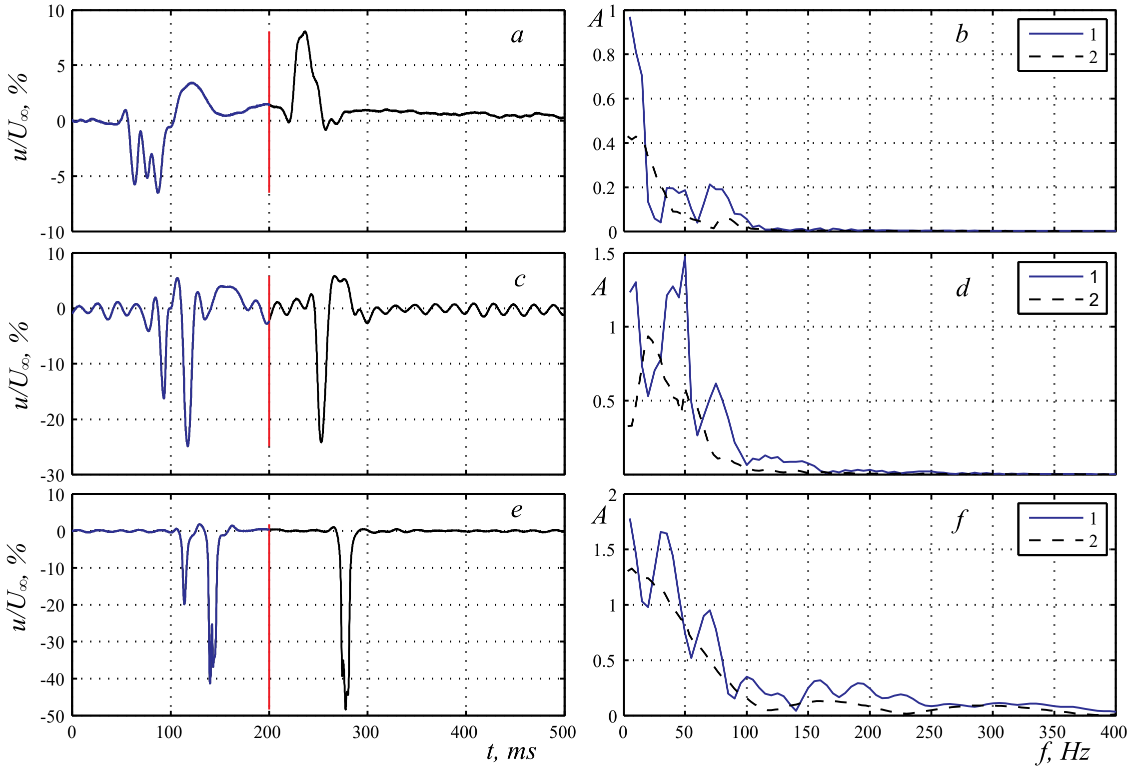

Figure 7: Hot-wire signal oscillograms (a, c, e) and their spectra (b, d, f) at z = 0 and x = 200 (a, b), 250 (c, d), and 300 mm (e, f); 1 and 2 are the spectra of the wave packets on the leading and rear fronts of the streaky structure, respectively.

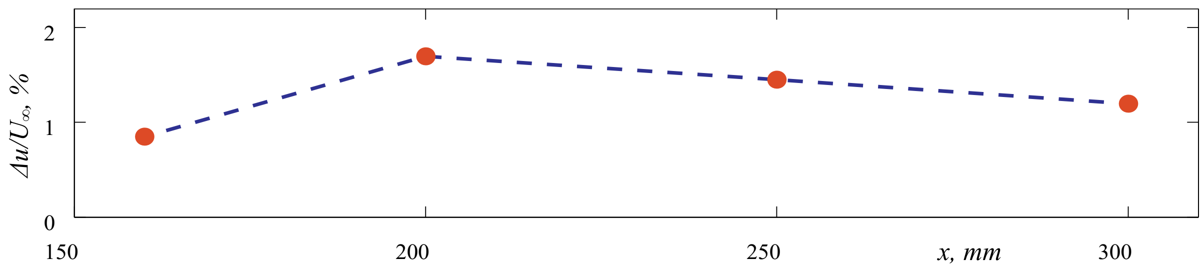

Figure 8: Longitudinal velocity deviations of the component in the central region of the streaky structure from its value in the unperturbed flow at a disturbance maximum over the y coordinate at z = 0.

9. Behind the step up to the x = 270 mm section the disturbance growth at the leading and rear fronts of the streaky structure is near-exponential. A similar result was obtained in the experiments [10], where spatially-localized disturbances were generated on a straight wing in the adverse pressure gradient region. Generally, the development of the wave packets under study corresponds to the present ideas on the separated flow stability. The flow destabilization accompanying boundary layer separation mentioned in the beginning of the paper manifests itself as an increase in the spatial growth rates of the instability waves, which can be as high as an order of magnitude, and as the broadening of the spectrum of amplifying disturbances. Obviously, such conditions are favourable for the growth of the wave packets generated in the near-wall flow under its localized low-frequency forcing.

Summary

The response of a flow with laminar boundary layer separation behind a rectangular backward-facing step to spatially localized low-frequency vibrations of the surface is determined.

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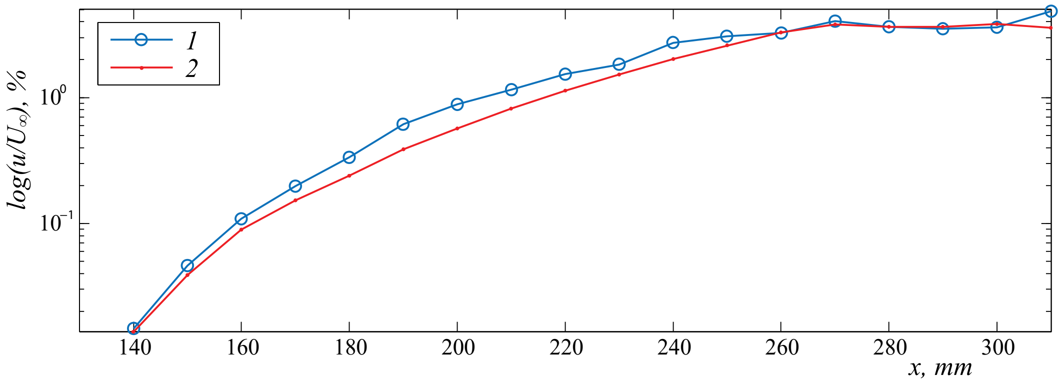

Figure 9: Oscillation amplitude variation along the flow in the frequency band from 26 to 400 Hz at a fluctuation maximum over the y coordinate at z = 0. 1 and 2 are the wave packets on the leading and rear fronts of the streaky structure, respectively.

The wall oscillations generate the disturbances of two types within the separation zone, which are characteristic of transitional shear flows, namely, instability wave packets and stream wise low-frequency deformations of the velocity field.

The process of laminar-turbulent transition behind the step is dominated by the wave packet growth at comparatively weak variations in the stream wise structures and, moreover, their decay with increasing distance from the step.

The comparison of the data obtained with the similar results for flow over a straight wing shows that boundary layer separation, as well as an adverse pressure gradient, stimulates the amplification of wave packets and their transformation into turbulent spots.

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References

[1] M.T. Landahl, “A Note on an Algebraic Instability of Inviscid Parallel Shear Flows,” J. Fluid Mech. **98**, 243 (1980).
[2] P.J. Schmid and D.S. Henningson, *Stability and Transition in Shear Flows*, Springer, New York (2001).
[3] E. Reshotko, “Transient Growth: A Factor in Bypass Transition,” Phys. Fluids 13, 1067 (2001).
[4] V.G. Chernoray, A.N. Spiridonov, M.M. Katasonov, and V.V. Kozlov, “Disturbance Generation Using a Localized Vibrator in the Straight Wing Boundary Layer,” Journal of Applied Mechanics and Technical Physics. 42 (5), pp. 765-772, 2001.
[5] V.N. Gorev and M.M. Katasonov, “Generation and Development of Forerunners on the Fronts of Streamwise Structures in the Straight Wing Boundary Layer,” Thermophysics and Aeromechanics. V.11, №3, 391-403 (2004).
[6] V.N. Gorev, M.M. Katasonov, and V.V. Kozlov, “Wave Forerunners of Streamwise Structures on Straight and Swept Wings,” Dokl. Ross. Akad. Nauk 410, 53 (2006).
[7] V.N. Gorev, M.M. Katasonov, and V.V. Kozlov, “Wave Forerunners of Streamwise Structures in a Swept Wing Boundary Layer,” Fluid Dynamics 42 (5), 732 (2007).
[8] V.N. Gorev, M.M. Katasonov, and V.A. Shcherbakov, “Experimental Investigation of Generation and Development of Wave Packets, as Forerunners of Localized Disturbances in Two-Dimensional and Three-Dimensional Boundary Layers,” Vestn. Novosibirsk Gos. Un-ta. Ser. Fizika 2 (4), 49 (2007).
[9] A V.N. Gorev, M.M. Katasonov, and V.V. Kozlov, “Specific features of unsteady processes in the front regions of streaky structures in the boundary layer on a nonswept wing”. Thermophysics and Aeromechanics. V.15, №3, 415-425 (2008).
[10] M.M. Katasonov, P.A. Motyrev, D.S. Sboev, V.V. Kozlov, and K.B. Evers, “Development of the Wave Packets-Forerunners in the Straight Wing Boundary Layer,” Vestn. Novosibirsk Gos. Un-ta. Ser. Fizika 7 (1), 28 (2012).
[11] H. Schlichting, *Boundary Layer Theory*, McGraw-Hill, New York (1969).
[12] H. Taghavi and A.R.Wazzan, “Spatial Stability of some Falkner–Skan Profiles with Reversed Flow,” Phys. Fluids 17, 2181 (1974).
[13] A.H. Nayfeh, S.A. Ragab, and A.A. Al-Maaitah, “Effect of Bulges on the Stability of Boundary Layers,” Phys. Fluids 31, 796 (1988).

DOI: 10.13009/EUCASS2017-210

[14] A. Michalke, “On the Inviscid Instability of Wall-Bounded Velocity Profiles Close to Separation,” Z. Flugwiss. Weltraumforsch. 14, 24 (1990).
[15] A.V. Boiko, G.R. Grek, A.V. Dovgal, and V.V. Kozlov, *The Origin of Turbulence in Near-Wall Flows*, Springer, Berlin (2002).
[16] A.V. Boiko and A.V. Dovgal’, “Instability of Local Separation Flows against Small-Amplitude Disturbances,” Izv. Sib. Otd. Ross. Akad. Nauk No. 3, 19 (1992).