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APPLICATION OF FLOW SUCTION FOR CONTROLLING THE SHEDDING OF LARGE-SCALE VORTICES AT BOUNDARY-LAYER SEPARATION

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A wind-tunnel study of the influence of flow suction on laminar boundary-layer separation behind a two-dimensional step on the surface is performed. Hot-wire measurements are carried out at low subsonic flow velocities. It is demonstrated that this method of flow control allows suppressing the formation of large-scale vortices determined by global stability properties of the separation region.

Key words: *boundary-layer separation, vortex shedding, suction, separation control.*

Emergence of local regions of laminar-flow separation (so-called separation bubbles) is often accompanied by generation of large-scale vortices, which are quasi-periodically shed from the separation zone in the external flow direction. Dominating in the unsteady flow, the vortices determine its fluctuating and, to a large extent, mean (time-averaged) parameters, which can be optimized by affecting the formation and dynamics of coherent vortex structures.

The vortex motion emerging owing to evolution of disturbances of the separated shear layer can be controlled by changing their initial spectrum and local characteristics of flow stability. The initial spectrum of perturbations is modified by periodic excitation of the separation region by external acoustic forcing [1, 2] or locally generated oscillations [3, 4]. The stability of the separated flow to small-amplitude oscillations can be changed, e.g., by flow suction or by cooling of the body surface [5–7].

A possibility of controlling quasi-periodic vortex formation is considered in the present paper, the vortices being induced by instability of the separation region to long-wave oscillations ("shedding"-type instability in terminology of [8]) rather than amplification of convective disturbances of the separated layer. The coherent vortex motion determined by the global flow properties at the scale of the entire separation region was examined experimentally in [9, 10]. One method of controlling flow separation in such a regime of instability was considered in [11], where vortex formation was found to depend on weak harmonic excitation of the flow in the frequency range of amplifying small perturbations of the separated boundary layer.

A possible method of affecting the shedding of periodic vortices used in the present work is flow suction, which is a well-known flow-control technique, in particular, for modification of the transition to turbulence initiated by flow instability behind the boundary-layer separation point [5].

Experimental Technique. The experiments were performed in a T-324 low-turbulent subsonic wind tunnel located at the Institute of Theoretical and Applied Mechanics of the Siberian Division of the Russian Academy of Sciences. The wind tunnel has a closed test section $1 \times 1 \times 4$ m, and the free-stream turbulence is lower than 0.04%. The experimental model schematically shown in Fig. 1 was previously used to study the formation of coherent vortices in the flow behind a rectangular step on a flat-plate surface [9–11]. The model consisting of two plates was mounted in the centerplane of the wind-tunnel test section at a zero angle of attack, and the level of background fluctuations of the boundary layer ahead of the step of height $h = 2.9$ mm was minimized by a trailing-edge flap. Suction of the near-wall flow was performed through a transverse slot 70 mm long and 0.4 mm wide, which was

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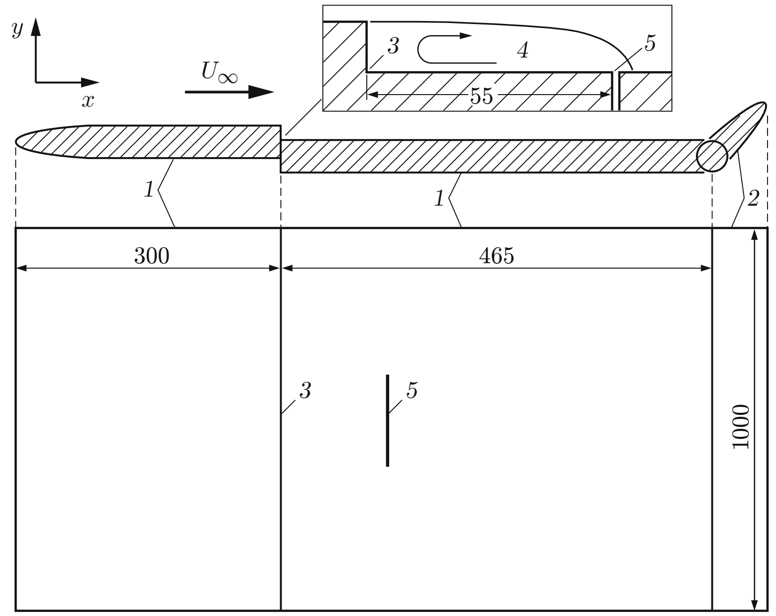

Fig. 1. Experimental model: 1) plates; 2) flap; 3) step; 4) separation region; 5) suction slot.

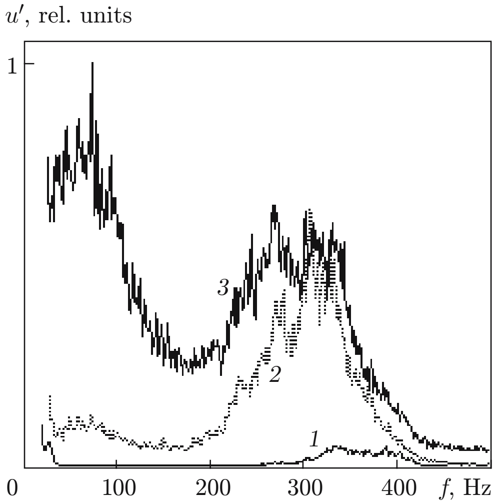

Fig. 2

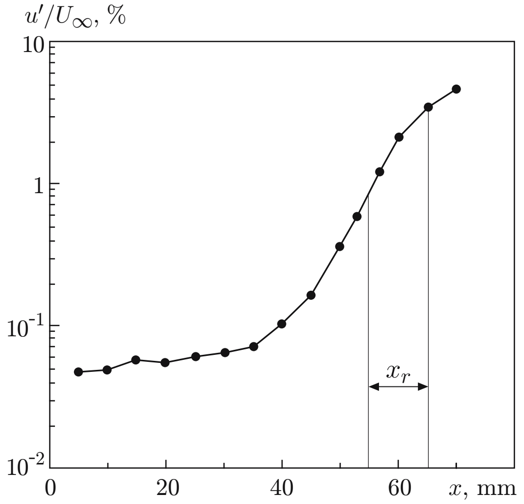

Fig. 3

Fig. 2. Disturbances of the separated flow: 1) $x = 40$ mm and $y = 2.6$ mm; 2) $x = 50$ mm and $y = 2.8$ mm; 3) $x = 54$ mm and $y = 2.0$ mm.

Fig. 3. Streamwise variation of the maximum root-mean-square amplitude of oscillations in the frequency band $f = 25$–100 Hz corresponding to shedding of quasi-periodic vortices.

located at a distance of 55 mm behind the step on the surface of the rear plate symmetrically with respect to the centerplane of the latter. Under the chosen test conditions, the slot was located in the region of reattachment of the separated layer, where large-scale vortices are formed. Suction intensity was controlled by a flow-rate meter.

The flow characteristics were determined by measuring the longitudinal velocity component by an AN 1003 constant-temperature hot-wire anemometer and single-wire probes. The hot-wire signal digitized by a 12-digit analog-to-digital converter was processed on a personal computer in the MATLAB environment. The hot-wire probe in the examined flow region was traversed automatically with an error smaller than 2.5 μm. The main measurements were performed in the plane of symmetry of the model; in the coordinate system used below, the x

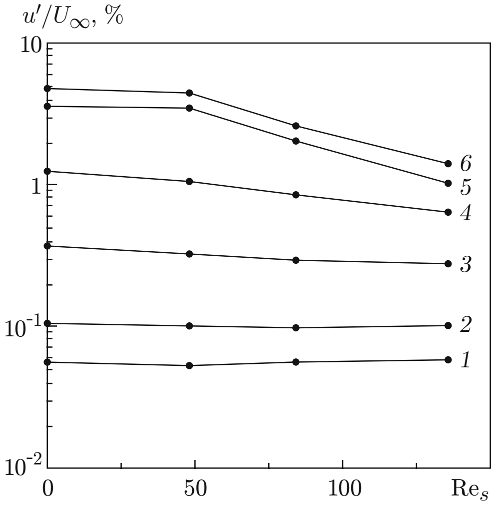

Fig. 4

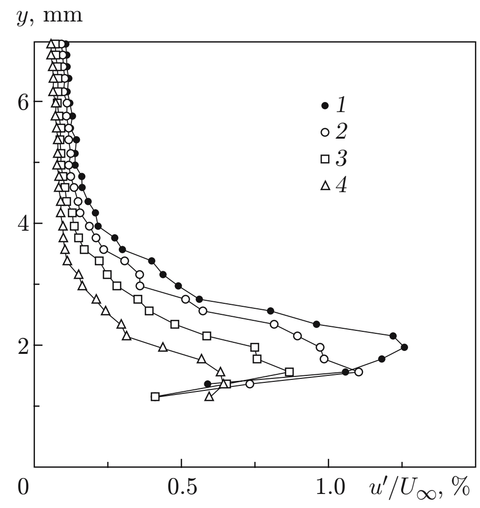

Fig. 5

Fig. 4. Maximum amplitude of low-frequency oscillations in the frequency band $f = 25$–100 Hz during suction for $x = 20$ (1), 40 (2), 50 (3), 57 (4), 65 (5), and 70 mm (6).

Fig. 5. Profiles of disturbances in the frequency band $f = 25$–100 Hz during suction ($x = 57$ mm) for $\mathrm{Re}_s = 0$ (1), 48 (2), 84 (3), and 136 (4).

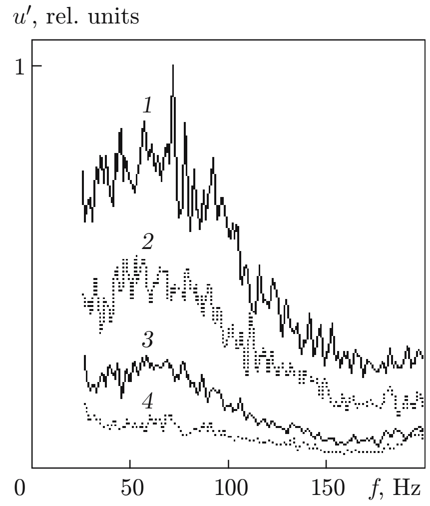

Fig. 6

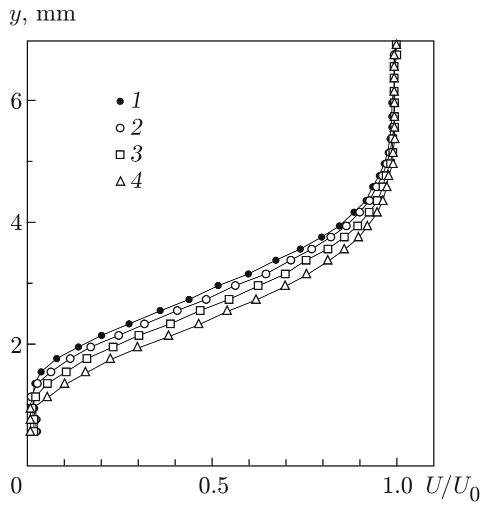

Fig. 7

Fig. 6. Suppression of oscillations at the vortex-shedding frequency at the point $x = 54$ mm, $y = 2$ mm (notation the same as in Fig. 5).

Fig. 7. Mean velocity profiles in the separation region during flow suction with different rates at $x = 50$ mm (notation the same as in Fig. 5).

coordinate stands for the streamwise distance from the step, and the y coordinate is measured normal to the wall from the surface of the rear plate.

Test Results. The characteristics of the separated flow under conditions close to those used in the present experiments were considered in detail in [9, 10]. The velocity of the external flow above the step being $U_\infty = 9$ m/sec (Reynolds number $\mathrm{Re}_h = U_\infty h/\nu = 1650$, where ν is the kinematic viscosity), the laminar boundary layer was separated with a displacement thickness $\delta_1 = 0.89$ mm, momentum thickness $\theta = 0.39$ mm, and shape factor $\delta_1/\theta = 2.26$ at a distance $x = -5$ mm. Flow separation was accompanied by its reattachment to the model surface at $x_r = 55$–65 mm and a subsequent transition to the turbulent flow regime. The evolution of disturbances in the separation region is illustrated in Fig. 2. Perturbations of two scales dominate in the spectra: high-frequency oscillations (instability waves of the separated layer) and low-frequency oscillations (spectral image of large-scale vortices). High-frequency oscillations are identified among background disturbances in the upstream part of the separated flow, whereas low-frequency oscillations start increasing close to the reattachment region (Fig. 3).

The development of low-frequency oscillations in a controlled flow was studied at several suction rates characterized by the Reynolds number $\mathrm{Re}_s = Ql/\nu$ (Q is the volume flow rate of sucked air and l is the slot length). Uniformity of suction over the model span was verified by special measurements, which showed that the changes in the mean flow velocity and intensity of oscillations along the slot are within 5%.

It follows from the data plotted in Fig. 4 that flow suction does not lead to any significant changes in the amplitude of low-frequency oscillations in the initial part of the separation region, suppressing the growth of oscillations at $x > 40$ mm. The effect of suction becomes more pronounced with increasing Re_s and reaches the maximum degree behind the region of reattachment, where the intensity of oscillations at the vortex-shedding frequency decreases almost fourfold under the present test conditions. It is seen from Fig. 5 that oscillations are suppressed over the entire thickness of the viscous layer $\delta = 5.39$ mm determined from the condition $U = 0.99U_0$, where U_0 is the local free-stream velocity (in the vicinity of the body surface, the data are not given because the method used does not allow obtaining correct quantitative results in this region for low mean flow velocities comparable with the disturbance amplitude). The effect of suction on shedding of large-scale vortices is also demonstrated in Fig. 6.

Apparently, the effect of suction on vortex generation, which was observed in the present experiments, is caused by the influence of suction on the time-averaged characteristics of the separation region. The general trend found in computations implies the transition from the steady flow regime to the unsteady one with periodic vortex formation in local separation regions as the size of the latter increases [12–14]. The data obtained in these studies correlate with the results of the stability analysis, which predicts origination of global modes of oscillations in rather large regions of boundary-layer separation [15]. With allowance for the results of these papers, flow suction, which decreases the thickness and, correspondingly, the length of the separation region (Fig. 7), can be assumed to stabilize the latter with respect to shedding of large-scale vortices. In this sense, the control method discussed is similar to that used in the experiments of [11], where the diminution of the separation region and a modification of vortex motion were reached by generation of instability waves of the separated boundary layer.

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