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INTERACTION OF LARGE-SCALE AND SMALL-SCALE OSCILLATIONS DURING SEPARATION OF A LAMINAR BOUNDARY LAYER

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The mutual influence of short-wave oscillations (instability waves of the separated boundary layer) and long-wave disturbances at the frequency of shedding of periodic large-scale vortices is experimentally studied in flow separation behind a step. The possibility of controlling the process of vortex formation by exciting amplifying disturbances in the shear layer is demonstrated.

Key words: *flow separation, instability, vortex shedding, separation control.*

Introduction. Hydrodynamic instability in regions of the laminar boundary-layer separation leads to the development of unsteady motion, which can involve velocity disturbances of various scales. The latter include short-wave oscillations amplifying in the separated shear layer and long-wave oscillations at the frequency of periodic large-scale vortices generated in the separation region and entrained from this zone in the streamwise direction. Under these conditions, it is possible to control the fluctuating and, finally, time-averaged characteristics of separated flows by using periodic external forcing. Such an approach to flow-separation control was implemented in a number of studies with the use of various methods of exciting control oscillations for stimulating the transition to turbulence in a separated boundary layer and modifying the coherent vortex motion in regions of separation of a subsonic gas flow (see [1–6]).

According to the results of previous investigations, shedding of periodic vortices during flow separation can be caused by various reasons. One of them is the origination of vortex structures in the separated shear layer with a subsequent increase in their size as they propagate from the separation point to the region of reattachment [6–10]. In this case, the result of the external forcing is explained by the change in dynamics of vortices, including the processes of their coupling and multiple coalescence. Another mechanism of periodic vortex formation is associated with instability of the separation region to long-wave oscillations, which is controlled by large-scale flow properties [4, 11, 12]. If so, the flow characteristics behind the separation point are simultaneously determined by two phenomena of different nature: 1) amplification of high-frequency disturbances regulated by local properties of stability of the separated layer; 2) global vortex dynamics. Under these conditions, it becomes possible to control the unsteady flow field in regions of boundary-layer separation, using interaction of large-scale and small-scale oscillations. The objective of the present work was to experimentally verify this possibility.

1. Experimental Technique. The experiments were performed in a T-324 low-turbulent wind tunnel of 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. In the experiments, the flow turbulence was lower than 0.04% at oscillation frequencies higher than 2 Hz. The experiments were performed with a model consisting of two plates snapped together, which were located in the central plane of the test section at zero incidence (Fig. 1). The plate thickness was 10 mm, the span was 995 mm, the length of the front plate was 300 mm, and the length of the back plate was 465 mm. The nose part of the front plate was made in the form of two adjoint ellipses with the semiaxes ratio of 2 mm : 132 mm on the test surface of the model and 8 mm : 132 mm on the opposite side. The laminar boundary layer separated at the junction of the plates behind a rectangular backward-facing step. The

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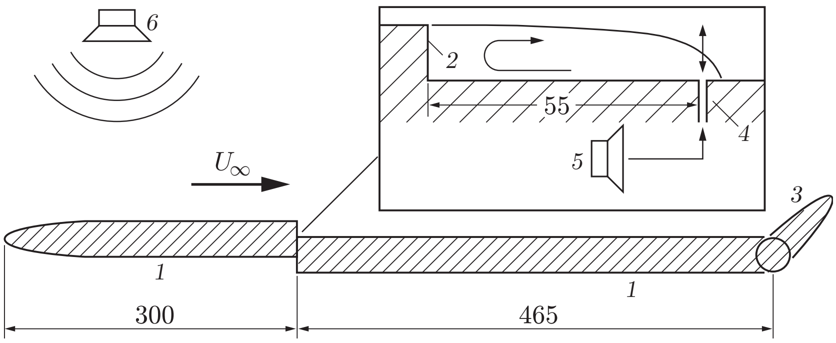

Fig. 1. Layout of the experiment: 1) plates; 2) step; 3) flap; 4) transverse slot; 5) loudspeaker; 6) external source of acoustic oscillations.

TABLE 1

h, mm	U_∞, m/sec	Re_h	δ_1/h	δ_1/θ	x_r/h	x_{tr}/h	Generation of oscillations
3.0	9.0	1730	0.30	2.25	18.3–21.7	33	Acoustic
2.9	9.0	1670	0.29	2.24	18.9–22.4	31	Local

streamwise pressure gradient in the vicinity of the leading edge of the model, which largely determines the state of the downstream flow, was controlled by a flap whose position was chosen in a manner that ensured a minimum possible level of background fluctuations of the boundary layer ahead of the step.

Interaction of instability waves of the separated boundary layer and oscillations arising in the course of formation of periodic vortices was examined under harmonic excitation of the flow at corresponding frequencies. The oscillations were generated by an acoustic source located on the wall of the wind-tunnel test section above the separation region or locally, through a transverse slot arranged in the back plate surface symmetric to the central section. The slot 70 mm long and 0.4 mm wide was located at a distance of 55 mm behind the step, in the region of reattachment of the separated layer. In this case, the source of oscillations was a dynamic loudspeaker connected with the slot by a pneumatic pipeline. The loudspeaker was placed downstream of the test model.

The mean and fluctuating components of flow velocity were measured by a DISA hot-wire anemometer (55 M01 main unit combined with a 55 M10 standard bridge) with the use of single-wire probes. The technique allowed obtaining the necessary quantitative results in the major part of the measurement region, except for the near-wall part of the separation region with low velocity of the backflow, where the probe data could serve to estimate the flow velocity. The hot-wire signal was digitized by an analog-to-digital converter and processed on a computer to determine the spectral characteristics of disturbances. The amplitudes of the fluctuating components were registered in a variable frequency band, which was relatively wide for wave packets growing behind the separation point and narrower in studying artificially excited disturbances; in the latter case, this procedure allowed us to reduce the contribution of background fluctuations to the probe signal. The measurements were performed in the plane of symmetry of the model; the x coordinate used in what follows is counted from the step in the streamwise direction.

2. Characteristics of the Examined Flow. The results described below were obtained in two experiments performed under similar conditions with external acoustic or local excitation of the separated flow. The main parameters of the flow around the step in both cases are listed in Table 1: h is the step height, U_∞ is the velocity of the external flow above the step, $\mathrm{Re}_h = U_\infty h/\nu$ is the Reynolds number, and δ_1 and θ are the boundary-layer displacement thickness and momentum thickness measured upstream of the separation point ($x = -5$ mm). The approximate position of the reattachment zone of the separated layer x_r, which was determined from the mean-flow data obtained behind the step, and the coordinate of the "point" of transition to turbulence x_{tr}, which corresponds to the maximum of fluctuations in the near-wall region in the streamwise direction, are also listed in Table 1. In both cases, for these Reynolds numbers and a low level of external disturbances, the unstable flow in the separation region remains laminar, and the turbulent flow around the model appears in the boundary layer behind the region of reattachment.

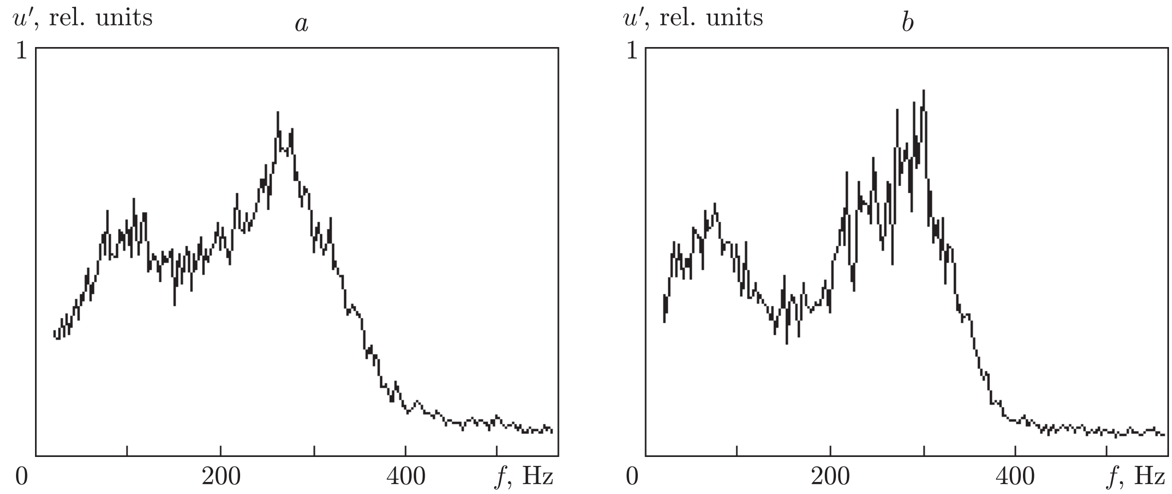

Fig. 2. Spectra of disturbances: (a) $h = 3.0$ mm and $x/h = 18.7$; (b) $h = 2.9$ mm and $x/h = 20.0$.

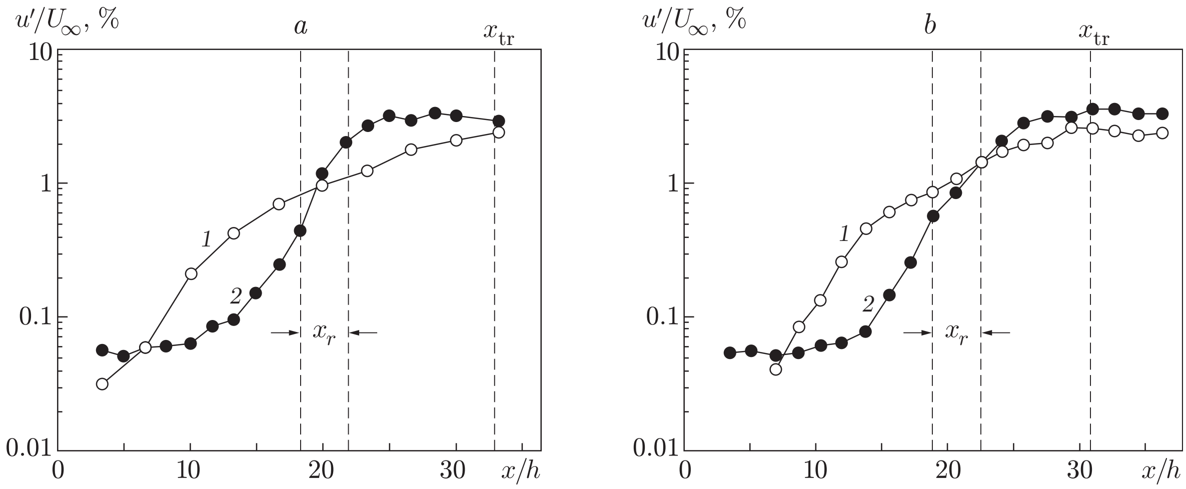

Fig. 3. Downstream amplification of disturbances: (a) $h = 3.0$ mm and $f = 290$ (1) and 100 Hz (2); (b) $h = 2.9$ mm and $f = 290$ (1) and 75 Hz (2); the amplitudes are measured in the band of 15 Hz.

The amplitude spectra of perturbations behind the boundary-layer separation point are shown in Fig. 2. The data were obtained in the maximum of disturbances along the normal coordinate, corresponding to the value $U/U_0 \approx 0.5$, where U_0 is the local velocity of the external flow, which differs from U_∞ within 2.5% in the separation region. The growth of instability waves of the separated shear layer and vortex formation are presented in the spectra by packets of high-frequency and low-frequency disturbances, respectively. Their central frequencies are close to 270 and 100 Hz in one case (Fig. 2a) and to 290 and 75 Hz in the other case (Fig. 2b). The difference in spectral data obtained in two similar experimental regimes is, probably, caused by the effect of uncontrolled external perturbations, including turbulent, acoustic, and vibrational ones, on disturbances naturally arising in the separated flow. The growth of disturbances in the range of separated layer instability and at the frequency of vortex shedding measured at $U/U_\infty \approx 0.5$ in the streamwise direction, is shown in Fig. 3. With distance from the step, high-frequency oscillations are first amplified. The formation of large vortices dominating further downstream begins close to the reattachment region. This separated flow regime with two types of instability (short-wave and long-wave instabilities) was studied in previous experiments [11, 12].

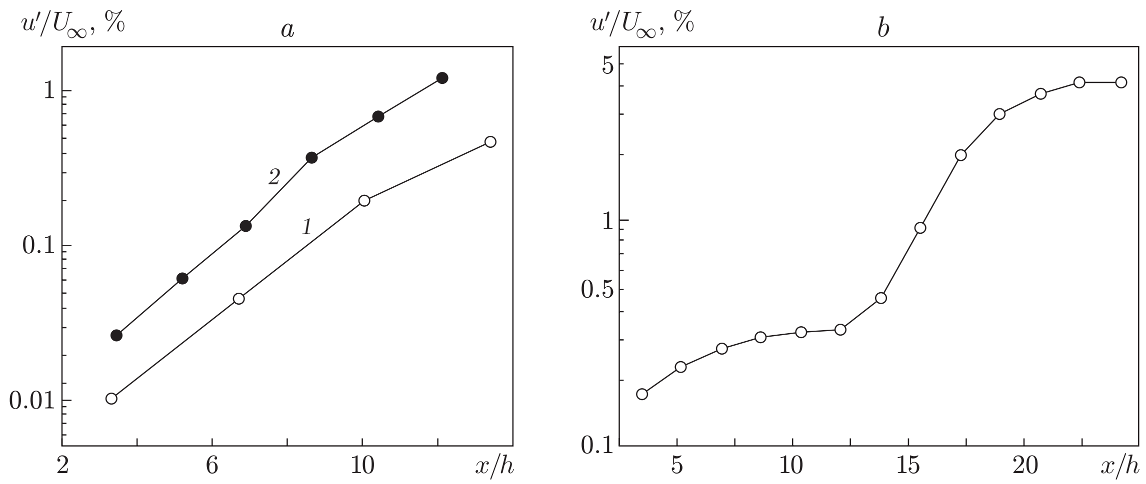

Fig. 4. Amplitudes of oscillations excited in the separation region: (a) $h = 3.0$ (1) and 2.9 mm (2), generation frequency 290 Hz; (b) $h = 2.9$ mm, generation frequency 75 Hz; the data were obtained in the band of 2 Hz.

3. High-Frequency Generation. Excitation of oscillations at the frequency of instability waves of the separated layer (by an external acoustic source or by periodic injection of a gas through the slot in the model surface) gives rise to vorticity disturbances in the vicinity of the step, which are close to two-dimensional ones and propagate in the streamwise direction [12]. The effect of these disturbances on formation of large-scale vortices was studied in two regimes with different generation amplitudes (Fig. 4a). In both cases, the flow was subjected to weak periodic forcing at which the disturbances introduced into the separation region behave initially as exponentially growing linear oscillations.

The measurement of the fluctuating component of flow velocity showed that the external acoustic and local generation of instability waves yields an identical result: the intensity of disturbances at the vortex-shedding frequency increases in the separation region and decreases behind the reattachment zone. As an illustration, Fig. 5 shows the spectral data obtained in the maximum of disturbances across the viscous layer. The quantitative characteristic of the effect observed can be obtained from the streamwise distributions of the amplitude of low-frequency oscillations in Fig. 6. In particular, the decrease in the amplitude of oscillations at the vortex-shedding frequency in the reattached flow reaches 20–30%.

With allowance for the previous investigations of unstable separated flows, the results of the present study can be explained as follows. Since the formation of the separation region is related to the laminar–turbulent transition, generation of instability waves is accompanied by a change (diminution) of the circulation-region size. This, in turn, affects the dynamics of large vortices, which is determined by flow properties in the scale of the entire separation bubble. Thus, the effect of high-frequency oscillations on vortex motion stems up from their influence on the time-averaged characteristics of the separated flow.

4. Low-Frequency Excitation. The results of preliminary tests revealed a low efficiency of the external acoustic excitation for generating oscillations at the vortex-shedding frequency; therefore, only the local source of periodic disturbances was used further. The streamwise distribution of the maximum amplitude of excited low-frequency oscillations in the main regime of subsequent measurements is shown in Fig. 4b. A comparison of these data with the dependence of the disturbance amplitude on the streamwise coordinate in Fig. 3b (curve 2) shows that the excitation produces low-frequency oscillations naturally arising in the separation region, but the intensity of these oscillations is higher.

A study similar to that described in Sec. 3 did not reveal any effect of low-frequency generation on the development of instability waves of the separated boundary layer beyond the experimental error. The result obtained does not exclude the possibility of such an effect at a higher intensity of excitation, which inducing oscillations of the shear flow, involves periodic variation of its local stability characteristics. At the same time, in the case of commensurable amplitudes of high-frequency and low-frequency oscillations generated in the separation region

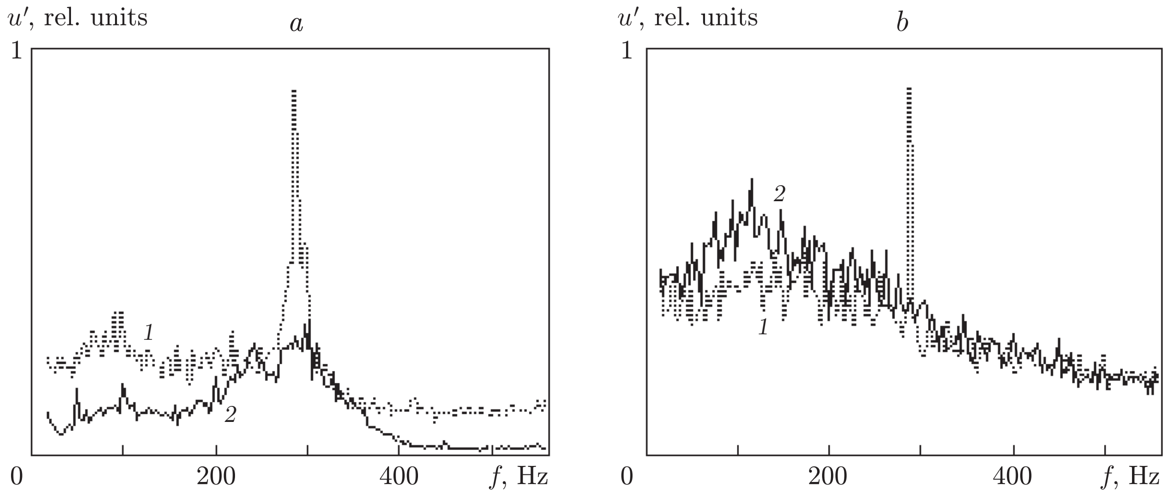

Fig. 5. Frequency spectra of oscillations ($h = 2.9$ mm) for $x/h = 17.2$ (a) and $x/h = 31.0$ (b); curves 1 and 2 refer to the flow with and without excitation, respectively.

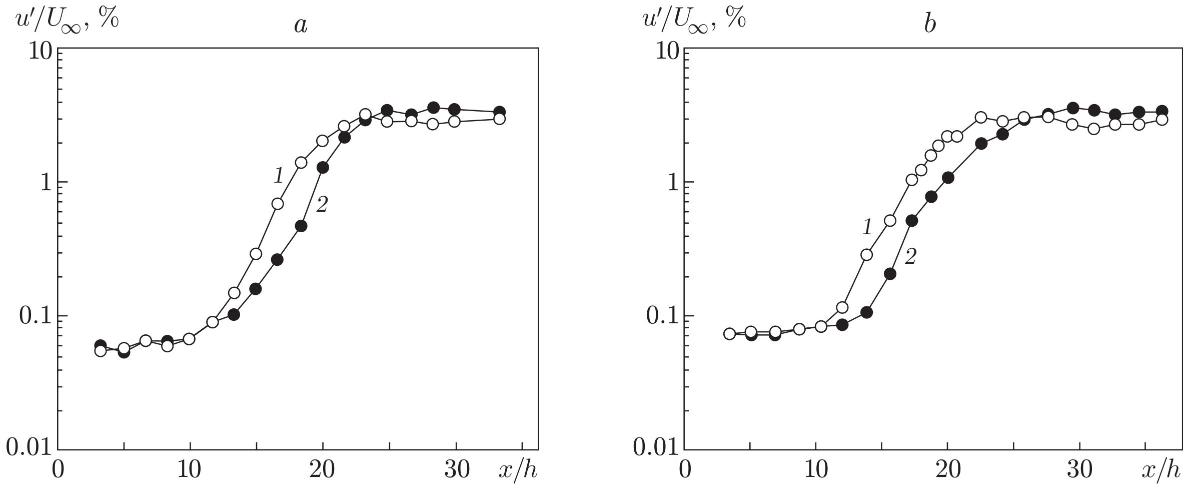

Fig. 6. Amplitudes of oscillations at the vortex-shedding frequency: (a) $h = 3.0$ mm and $f = 100$ Hz; (b) $h = 2.9$ mm and $f = 75$ Hz; curves 1 and 2 refer to the flow with and without excitation, respectively; the data are obtained in the band of 15 Hz.

(see Fig. 4), the effect of low-frequency oscillations on short-wave disturbances of the separated boundary layer is insignificant as compared to the reverse effect described in Sec. 3.

Conclusions. The results of the present experiments supplement the current notions on the possibility of controlling an unstable flow in regions of separation of a laminar boundary layer by means of external periodic forcing. During separation with simultaneous amplification of short-wave disturbances and shedding of large-scale periodic vortices, weak harmonic excitation at the frequency of oscillations close to the maximally growing disturbances in the range of linear instability of the separating boundary layer allows one to control the perturbations dominating in the low-frequency range of the spectrum.

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