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EXCITATION OF SELF-OSCILLATIONS IN FLOW PAST A SURFACE WITH A RECESS AND THE POSSIBILITY OF PREVENTING THEM

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The results of experimental investigations of acoustic radiation initiated by hydrodynamic perturbations at the inlet to a cavity on a surface with a stream flowing past it are analyzed. A comparison is made between the processes of formation of large-scale hydrodynamic vibrations in a shear flow shed from the leading edge of the junction of the recess with the surface past which a stream flows and the processes in the region of transition from a laminar boundary layer on the surface of a wing to a turbulent one. The advisability of division of the flow inhomogeneity in the zone of the junction in order to prevent or weaken self-oscillations in the flow is estimated.

The problem of excitation and suppression of self-oscillations in service lines involving dead-end branches and in recesses on a surface with an external flow past it has a purely practical background. Experience has shown that high-level pressure pulsations and associated vibrations are a dangerous loading for the elements of the binding of main gas-compression stations [1] and of some special constructions of flying vehicles.

In the two-dimensional hypothetical model [2] of a self-oscillating system it is assumed that in the region of the junction of a recess with a surface — the boundary of a shear flow — hydrodynamics waves of instability appear which interact with the rear edge of the recess and which, in so doing, generate narrow-band acoustic disturbances. The latter are enhanced by the recess-resonator and, in turn, increase the amplitude of hydrodynamic vibrations upstream of the flow near the leading edge of the recess. Thus, the acoustic feedback closes the self-oscillating system.

It should be noted that the narrow-band acoustic radiation becomes noticeable against the background of the continuous spectrum of the noise generated by the flow as a result of the large-scale character of associated hydrodynamic vibrations of the same frequency in the flow inhomogeneity considered. Precisely this fact was taken into account in [1], where, using a model of a channel with one dead-end branch, a grating of plates oriented along the main flow was installed at its inlet which decrease the scales of periodic structures. Usually, this allowed one to prevent or substantially weaken self-oscillations in the flow [1].

At the same time, installation of a similar grating of plates in the model that in the main reproduced the rectangular channel between the fuselage surface and the tank inside it appeared inefficient. This fact indicates that the formation of the fundamental notion of the mechanism of self-oscillations in the system considered has not been completed. A further experimental research of self-oscillations which would expand these notions is needed, as well as the carrying out of an analysis that would also include the data of [3].

Precisely the latter is the aim of the present work, in which we consider a change in narrow-band pressure pulsations at a single value of Reynolds number, different depths of the dead-end branch, and on installing a grating of plates at its inlet. On the basis of experimental data it is assumed that at other Reynolds numbers the character of these changes will not differ in principle from that observed here.

1. In order to investigate self-oscillating processes, as in [1], a small closed-type wind tunnel with an open working section and with the diameter of a small cylindrical section at the exit from the nozzle equal to 150 mm was used. Model 1 of a tube-collector of the same diameter d_c = 150 mm and of length 120 mm was installed directly at the nozzle cut. The leading edge of the dead-end branch of diameter d_d = 53 mm was 24 mm downstream of the plane of junction of the nozzle with the tube-collector. The axis of the branch was normal to the collector axis; the

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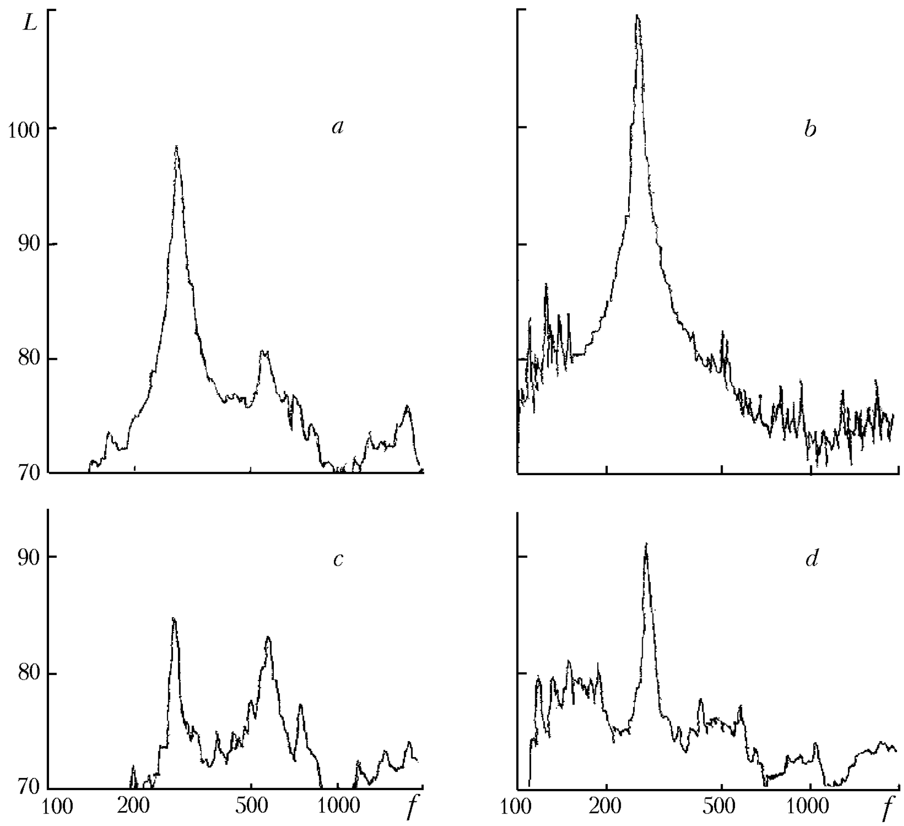

Fig. 1. Spectra of pressure pulsations $L(f)$ which correspond to: a) model 1 without a grating of plates at the junction of tubes, Sh = 0.379, $\bar{t}$ = 0.220; b) model 2 without a grating of plates, Sh = 0.354, $\bar{t}$ = 0.209; c) model 1 with a grating of plates at the junction of tubes, Sh = 0.373, $\bar{t}$ = 0.217, Δh = 0; d) model 2 with a grating of plates, Sh = 0.372, $\bar{t}$ = 0.216, Δh = 0. L, dB; f, Hz.

rounding-off radius of the junction of two tubes was virtually equal to zero. Model 2 differed from model 1 in that the branch was located on a fragment of the tube-collector which was an extension of the nozzle wall in the circle sector all along 120^o azimuth. The depth t of the dead-end branch was changed by shifting in it an insert resembling a piston in a cylinder.

To prevent self-oscillations in the channel of the wind tunnel itself a honeycomb was installed in front of the inlet into its diffuser [4]. The flow velocity on the axis of the model of the tube-collector at the exit from it was determined from the readings of a micromanometer connected with a Pilot tube; in experiments it was equal to $V \approx$ 38.8–39.5 m/sec. The Reynolds number Re = Vd_c/ν was equal to (3.7–3.9)$\cdot 10^5$.

To measure the pulsations of pressure p we used a 00026 noise meter with an MK201/MV201 capacitor microphone, a 02013 RFT self-recorder, a 01025 "Robotron" narrow-band analyzer, and a C1-107 multimeter-oscillograph. Pressure pulsations were analyzed within a frequency range f = 2–2000 Hz, within which the main energy of oscillations falls, with a three-percent transmission band and a three-minute analysis. From the results of measurements we determined the frequencies f_p in narrow-band components of the spectra of pressure pulsations $L(f)$, their level L_n, Strouhal number Sh = $f_p d_d/V$, and the relative depth of the dead-end branch $\bar{t} = tf_p/a$.

In all of the tests the microphone was located beyond the flow, above the free jet; its net was moved away from the axis of the working section of the tunnel by 370 mm; the axis of the microphone was normal to the working section axis and was 85 mm downstream of the model cut. The results of measurements by the microphone in one given section made it possible to obtain an idea of the occurring processes.

2. First of all, it was established in the experiments that the spectra of pressure pulsations for the depth t = 0 of the dead-end branch do not contain narrow-band components that appear in the wind tunnel itself and which are

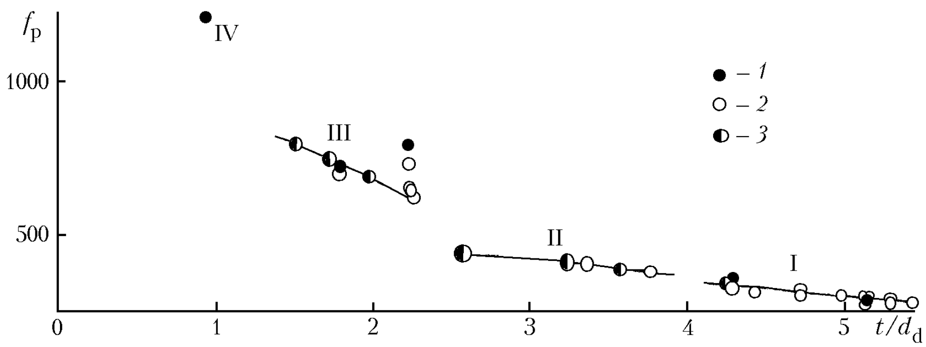

Fig. 2. Frequencies of narrow-band perturbations f_p vs. the relative depth of the dead-end branch t/d_d within the range I–IV: 1) model 1 without a grating of plates; 2) model 2 without a grating of plates; 3) model 2 according to [1]. f_p, Hz.

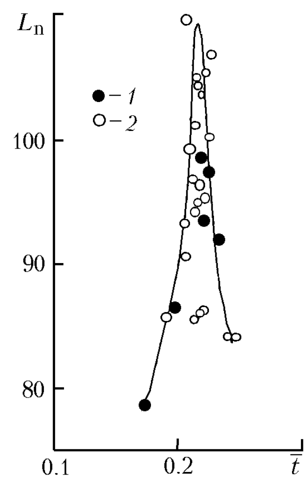

Fig. 3. The level L_n of the narrow-band component of the spectrum of pressure pulsations vs. the relative depth of the dead-end branch $\bar{t}$ without a grating of plates: 1) model 1; b) model 2. L_n, dB.

capable of influencing, in any way, the results of tests at $t \neq 0$. Then, in more detail than was done in [1], on models 1 and 2 pressure pulsations initiated by an initial source of periodic hydrodynamic perturbations in the dead-end branch were investigated, without a grating of plates and with branches of different depths. For the self-oscillations observed on spectra in the experiments there corresponded narrow-band components more prominent against the general background (Fig. 1), and, with other conditions being equal, most often differing in the level in measurements on models 1 and 2. Their frequencies f_p depended differently on the relative depth of the dead-end branch t/d_d in different ranges of its measurements, with the transition from one dependence to another sometimes occurring with a discontinuity (Fig. 2).

It should be noted that self-oscillating regimes in the present experiments are characterized by the value of the Strouhal number Sh and relative depth $\bar{t} = tf_p/a$, which correspond to the regions of realization of acoustic instability in the plane of the parameters Sh–$\bar{t}$ [5].

Of particular interest are the dependences of the levels of narrow-band oscillations L_n observed in the section of measurement on the relative depth of the dead-end branch $\bar{t}$ (Fig. 3) and on the Strouhal number Sh (Fig. 4). As is seen from Fig. 3, in the plane of the parameters L_n–$\bar{t}$ experimental points are located virtually in one region bounded by the curve of resonance type. Its maximum is at $\bar{t} \approx 0.22$ rather than at $\bar{t} = 0.25$, as might be expected. The latter seems to be due to the structure of hydrodynamic perturbations in their source, conditions of the propagation and reflection of acoustic disturbances in the experimental setup, and by the character of coupling between hydrodynamic and acoustic oscillations.

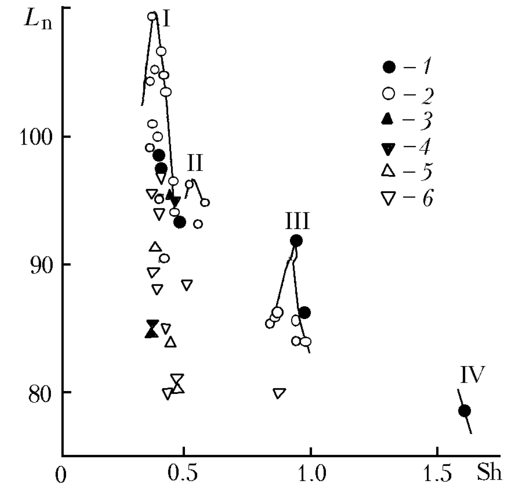

Fig. 4. The level L_n of the narrow-band component of the spectrum of pressure pulsations vs. the Strouhal number within the range I–IV: 1) model 1 without a grating of plates; 2) model 2 without a grating of plates; 3, 4) model 1 with a grating of plates with Δh = 0 and 7 mm; 5, 6) model 2, Δh = 0 and 7 mm. L_n, dB.

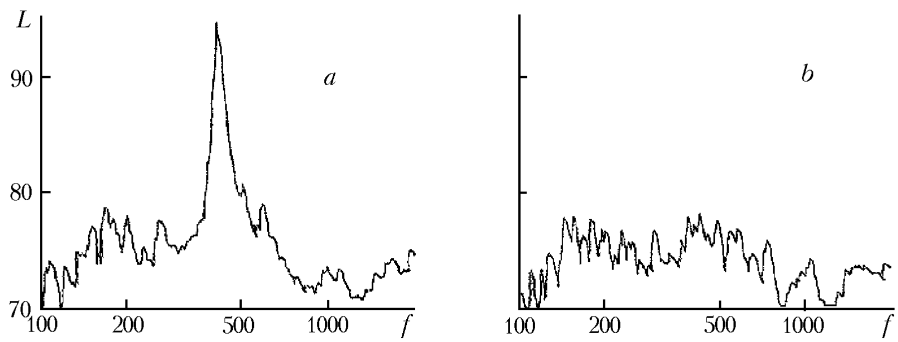

Fig. 5. Spectra of pressure pulsations $L(f)$ corresponding to: a) model 2 without a grating of plates at the junction of tubes, Sh = 0.564, t = 0.217; b) model 2 with a grating of plates, Δh = 7 mm. L, dB; f, Hz.

Unlike the foregoing, in the plane of the parameters L_n–Sh experimental points are located not in one region (Fig. 4) and clearly tend to values of Sh numbers close to $0.5n$, n = 1, 2, ... The latter fact was noted earlier in [1], and it was explained that the observed regularity owes its origin to $\lambda_h \approx d_d/n$ and $V_h \approx 0.5V$. The correspondence between the regions of the dependences L_n(Sh) in Fig. 4 to some individual changes in the frequency f_p of self-oscillations is designated by identical Roman digits in Fig. 2.

It appeared that the more detailed investigation of self-oscillations in the initial case was needed for the analysis of the processes occurring when a grating of plates is installed at the inlet to the dead-end branch. The grating consisted of five identically spaced plates of height 60 mm each oriented along the main stream. Three versions of the location of one of the two free edges of plates were considered (the two others came to the walls of the dead-end branch). In one case the edges of the plates were at the level of the collector generatrices, Δh = 0, in others they extended 7 mm and 18 mm into the collector.

Measurements of the spectra of pressure pulsations have confirmed the earlier noted effectiveness of flow division at the junction of the collector tubes and dead-end branch especially when the initial level of the narrow-band component L_n attained a maximum (Fig. 1). In the optimal case these components were not observed, after the plates had been installed in the dead-end branch, against the background of the continuous spectrum of pressure pulsations

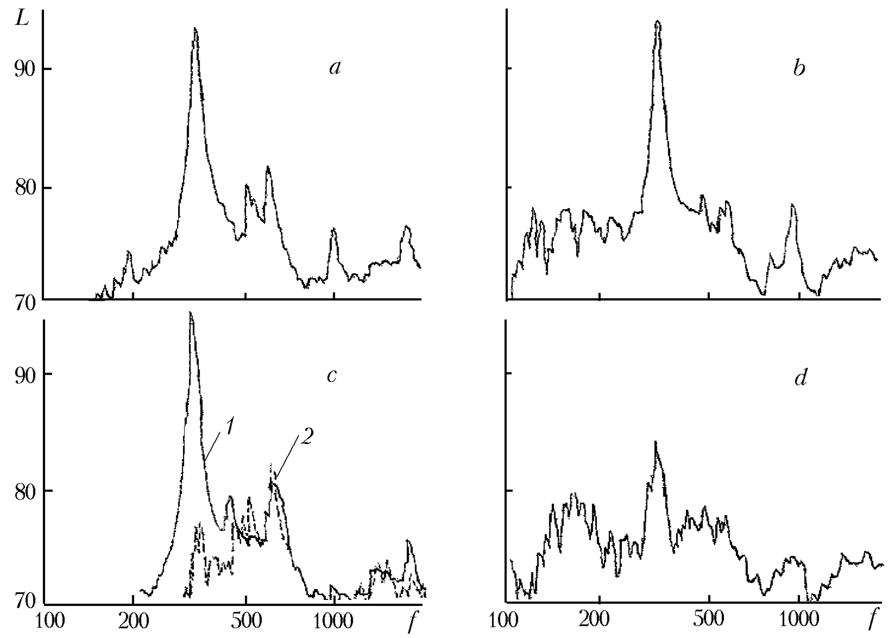

Fig. 6. Spectra of pressure pulsations $L(f)$ corresponding to: a) model 1 without a grating of plates at the junction of tubes, Sh = 0.455, t = 0.222; b) model 2 without a grating of plates at the junction of tubes, Sh = 445, t = 0.216; c) model 1 with a grating of plates at the junction of tubes (1), Sh = 0.428, t = 0.208 and model 1 with a transverse plate at the junction (2); d) mode 2 with a grating of plates at the junction, Sh = 0.444, t = 0.216. L, dB; f, Hz.

(Fig. 5) in zones III, IV, and partially in II or their level decreased by 10–20 dB in zones I, II (Fig. 4); in the latter case the frequency of the narrow-band components did not change or differed little from the initial one. The oscillograms obtained in the experiments demonstrate that harmonic or near-harmonic narrow-band pressure fluctuations that correspond to the initial structure of flow without gratings are smeared by stochastic pulsations when the gratings are used to prevent formation of large-scale hydrodynamic structures. Analogous results were also obtained on a large model of a man-hole in [3]. In the plane of the parameters L_n–t weakened self-oscillations are characterized by values that in the main do not extend beyond the region bounded by the resonance-type curve (see Fig. 3). Most often the values of t corresponding to them were close to 0.22.

However, in one case both on model 1 (t/d_d = 4.28) and on model 2 (t/d_d = 4.98) the acoustic radiation from the zone of hydrodynamic perturbations did not increase on installation of a grating of plates in the dead-end branch but even somewhat increased. At t/d_d = 4.28 in the initial case at identical depths of the dead-end branch and flows upstream of the junction in models 1 and 2 one observed very similar spectra of pressure pulsations and levels and frequencies of narrow-band components in the section where measurements were made (see Fig. 6a and c (spectrum 1) and 6b and d). But on division of the flow the intensity of narrow-band components at the junction was decreased only in model 2 (compare spectra a, c1 and b, d in Fig. 6). This points to the substantial role of the conditions of propagation and reflection of acoustic radiation beyond the source of hydrodynamic perturbations. Strictly speaking, in order to elucidate this fact, two models were used in the experiments. At the same time, now it is evident that the above-mentioned single case of the inefficiency of the installation of a grating at the junction was not accidental.

In the experiments carried out, the effectiveness of placing a grating of plates in the dead-end branch virtually did not depend on whether they extended ($\Delta h > 0$) into the tube-collector (model 1) or over the surface of its fragments (model 2) in the range of values of Δh considered. However, when the grating was buried, if only slightly, into the dead-end branch ($\Delta h < 0$), the effectiveness from its installation decreased sharply. The effectiveness also decreased in the case where a grating consisted of three plates oriented along the main stream.

The results presented indicate that one of the elements of the considered self-oscillating system that ensures the pumping of the flow energy into narrow-band acoustic disturbances is really large-scale hydrodynamic waves of instability in a relatively thin shear flow which sheds from the leading edge of the junction of tubes.

One cannot but notice a certain similarity between the hydrodynamic structures that channel the energy in the self-oscillating system considered and those formed under certain conditions of flow around an isolated wing [6]. In the latter case, at a small angle of attack, large-scale hydrodynamic waves of instability in a boundary layer on the windward side of the wing shed from it in the wake along with the turbulent boundary layer from the leeward surface. In the absence of any surfaces downstream of the wing an intense tone noise was generated in the flow. This very noise initiated hydrodynamic oscillations of the same frequency on the nose of the wing, thus accomplishing feedback. In both comparable cases, narrow-band pressure pulsations arise evidently because of the sharp change in the topology of large-scale periodic hydrodynamic structures.

3. It is evident that installation of a grating of plates in the dead-end branch is associated with minimum changes in the hydraulic resistance of the channel, and sometimes even with positive ones. However, as is established now, this method of influencing the structure of flow is not a universal means of combating self-oscillations in communications. Therefore, in the present work another possibility of preventing or weakening intense narrow-band pressure pulsations in a flow was also considered. It is also not universal, and it is based on the knowledge of the boundaries of the regions of realization of acoustic instability in the plane of parameters Sh–t [5].

At the given velocities of the main stream, diameter, and depth of the dead-end branch, we can determine, in the first approximation, the frequency of resonance oscillations and the values of t and Sh. If the latter values correspond to the region of realization of acoustic instability, there is a possibility to bring a regime from it by having changed the characteristic linear dimension of the entry into the dead-end branch, having installed, in it, one transverse plate normal to the vector of the main stream velocity, and having divided the entrance into the recess in half.

To avoid a substantial increase in the hydraulic resistance, the plate must not be transformed into an interceptor — its free edge must be situated at the level of the generatrices of the tube-collector or of its fragment. However, it should be kept in mind that then, on change in the velocity and (or) in the depth of the dead-end branch, self-oscillations may appear on such regimes where they were absent in the absence of the transverse plate in the initial case.

The corresponding experiment were carried out on models 1 and 2. In this case, the transverse plate divided in half the entrance into the dead-end branch in the direction of the main stream. The Strouhal number in this case was calculated from the characteristic linear dimension $d_d/2$ and was two times smaller than the initial one calculated from d_d. Measurements of the spectra of pressure pulsations in the indicated experiments fully confirmed the predicted results of installation of a transverse plate in a dead-end branch. Thus, for example, at $t/d_d = 2.23$ in model 2 the following values and the upper region of realization of acoustic instability [5] correspond to the initial regime: Sh = 0.978, $t = 0.246$, $L_n = 84$ dB. At a Strouhal number half as large and $t = 0.199$, corresponding to the investigated regime is the lower region of realization of acoustic instability [5], and as was expected a higher value of $L_n = 93.3$ dB. In contrast to this, at $t/d_d = 4.28$ in model 1 by installing a transverse plate in the dead-end branch the self-oscillations in the flow were practically prevented (compare Fig. 6a and c (spectrum 2)). In the latter example, corresponding to the regime parameters Sh = 0.455 and $t = 0.222$ is the lower region of realization of acoustic instability [5] from which the regime falls out when the Strouhal number decreases twice.

CONCLUSIONS

1. In the cases considered, the source that initiates the formation of a self-oscillating system in a flow is hydrodynamic waves of instability in a shear flow shed from the leading edge of entry into a dead-end branch.

2. Narrow-band acoustic disturbances in the system investigated may attain a maximum level at a relative depth of the branch not equal to one/fourth of the length of the energy-carrying acoustic wave.

3. Installation, in a dead-end branch at its inlet, of a grating of plates oriented along the main stream indeed weakens or prevents self-oscillations in many cases.

4. The effectiveness of the indicated means depends on the conditions of propagation and reflection of acoustic disturbances in the space that surrounds the local hydrodynamic inhomogeneity.

5. It is also possible to prevent self-oscillations in a flow bounded by a surface with a recess by dividing the inlet into the latter by a plate which is normal to the velocity vector of the main stream and which does not extend into the flow beyond the surface generatrices.

NOTATION

a, speed of sound propagation in a gas, m/sec; d_c and d_d, inner diameter of the tubes of the collector and of the dead-end branch, m; f, frequency of pressure pulsations, Hz; L, level of pressure pulsations, dB; p, pulsational component of an instantaneous values of pressure, N/m^2; Re, Reynolds number; Sh, Strouhal number; t, depth of the dead-end branch, m; V, flow velocity on the model axis, m/sec; V_h and λ_h, velocity of propagation and length of the wave of hydrodynamic perturbation in the zone of junction of the dead-end branch and the surface in a flow, m/sec and m; ν, coefficient of kinematic viscosity of a gas, m^2/sec. Subscripts and superscript: p, perturbation; h, hydrodynamic; c, collector; d, dead-end branch; n, narrow band; overbar, relative value.

REFERENCES

1. V. A. Vishnyakov, V. G. Zasetskii, R. K. Karavosov, A. G. Prozorov, and L. I. Sokolinskii, Generation and damping of flow oscillations in the region of a joint between a pipeline and a blind branch, *Inzh.-Fiz. Zh.*, **71**, No. 6, 1099–1106 (1998).
2. D. Rockwell and E. Naudascher, Review – Self sustaining oscillations of flow past cavities, *Trans. ASME*, **100**, No. 2, 152–165 (1978).
3. V. A. Vishnyakov, V. G. Zasetskii, R. K. Karavosov, A. G. Prozorov, and L. I. Sokolinskii, Appearance of narrow-band pressure pulsations and prevention of them in a tube with a dead-end cavity, *Tr. TsAGI*, Issue 2643, 93–102 (2003).
4. V. A. Vishnyakov and A. G. Prozorov, Excitation of pulsations of velocity and noise in a wind tunnel, *Mekh. Zhidk. Gaza*, No. 4, 165–172 (1992).
5. V. G. Zasetskii, R. K. Karavosov, A. G. Prozorov, and L. I. Sokolinskii, Study of interaction of disturbances in an internal flow, *Inzh.-Fiz. Zh.*, **77**, No. 5, 82–87 (2004).
6. A. G. Munin, A. G. Prozorov, and A. V. Toporov, Experimental investigation of the tone noise of flow around a wing at small flow velocities, *Uch. Zap. TsAGI*, **21**, No. 3, 28–37 (1990).