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HYDRODYNAMIC STRUCTURES — ELEMENTS OF THE SELF-SUSTAINED OSCILLATION SYSTEM IN THE FLOW

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The character of hydrodynamic disturbances in the near-wall shear flow inducing self-oscillations in the channel has been investigated. Experiments have been performed in a small and a large wind tunnel at a flow velocity of 10–40 m/sec. It has been found that excitation of self-oscillations becomes possible as a result of narrow-band acoustic radiation generation by not only vortex formations but also large-scale coherent structures in the region of the laminar-turbulent transition and in the turbulent boundary layer.

Keywords: *self-oscillations, acoustic, generation, disturbances, hydrodynamic, radiation, large-scale, laminar, reflection, transition, cavity, near-wall, grating, turbulent, experiment.*

Introduction. Self-oscillations in a subsonic flow with a niche-resonator on the surface restricting it arise due to the formation in the flow nonuniformity zone of a hydrodynamic source of acoustic disturbances. In the system under discussion, acoustic oscillations implement feedback that increases the amplitude of hydrodynamic pulsations upstream of the source and further downstream in its proper. Accordingly, damping or suppression of self-oscillations is achieved by changing the structure of the flow in the region of its nonuniformity or the resonator characteristics.

In this connection, notions about the character of the hydrodynamic structures generating acoustic radiation turn out to be important. In the review [1], in particular, it is assumed that acoustic radiation arises when the instability waves in a detached flow in the mouth of the dead-end cavity come in contact with the downstream edge of the niche. Unlike this, in [2], with account for the results of investigations of vortex formations [3, 4], it is assumed that precisely these waves generate narrow-band tonal noise and induce self-oscillations.

Up to now it has been possible to influence the intensity of the self-oscillations under consideration and prevent them altogether only knowing that they are excited as a consequence of the formation in the flow of large-scale coherent structures upon its separation from the front edge of the niche. In line with this idea is, in particular, also the lowering of the level of pressure pulsations in the flow when it is divided in the mouth of the niche and inside it by a grating from plates oriented along the undisturbed flow velocity vector [5]. However, a decrease in the scales and a change in the topology of coherent structures at the inlet to the dead-end cavity did not always lead to a positive effect. The reason could be both the inaccurate choice of design parameters of the grating from plates and the presence in the flow, apart from the above-mentioned sources, of other hydrodynamic sources of acoustic radiation on which the grating practically had no effect.

The aim of the present investigation was to determine what structures existing in the near-wall shear flow should be taken into account in the presence of a dead-end cavity on the flow-restricting surface.

Methods of Investigation. Most experiments were performed in a small wind tunnel TT-1 [5] with a closed loop and an open working section. The nozzle of the tunnel provides an eightfold compression of the flow and has an outlet diameter d_n = 150 mm. Excitation of self-oscillations in the wind tunnel proper was prevented by a cellular panel with a hole in the center of diameter 140 mm set at the inlet to the ring around the diffuser [6].

A baffle of length 118 mm whose cylindrical surface within the azimuth angle of 120^o was an extension of the nozzle wall was joined to the nozzle exit section [5]. The flow around the baffle, as was established in [5], was not followed by any separations. On the baffle surface, at a distance of 22 mm downstream from the nozzle-baffle joint there was a cylindrical blind branch of diameter d_d = 55 mm. Its axis was perpendicular to the axis of the open working section of the wind tunnel and to the baffle surface. The depth t of the branch was varied by displacing its bottom within 0–305 mm.

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In experiments, the flow velocity in the open working section of the small wind tunnel was $V \approx 17–39$ m/sec, and the Reynolds numbers $\mathrm{Re} = Vd_n/\nu$ were $(1.8–4.0)\cdot 10^5$. Worthy of notice is one important fact — the boundary layer on the wall of this tunnel nozzle was practically laminar before the outlet to the open working section [7]. On the baffle surface in the near-wall shear flow a laminar-turbulent transition was initiated but not completed [5].

In addition to the investigations in a small wind tunnel, we performed experiments in a large wind tunnel T-5. It also has a closed loop and an open working section; the degree of flow compression inside the nozzle was 5.32, and its outlet diameter was 2.2 m. In the considered range of velocities $V = 10.4–40.7$ m/sec and at Reynolds numbers $\mathrm{Re} = (1.5–5.8)\cdot 10^6$ the boundary layer on the nozzle wall before the inlet to the open working section was turbulent [8]. A baffle of length 1000 mm whose cylindrical surface was an extension of the nozzle wall was joined to the nozzle exit section with in an azimuth angle of 63°. At a distance of 277 mm downstream from the nozzle exit section, on the baffle surface there was a rectangular inlet into the dead-end cavity. Its downstream length was 450 mm and the width was 250 mm.

To measure pressure pulsations p and their frequency spectra $L(f)$, we used, as earlier in [5], a 00026 noise meter with an MK201/MV201 capacitor microphone, a 02013 RFT recorder, a 01025 "Robotron" narrow-band analyzer, and a C1-107 multimeter oscilloscope. Pressure pulsations were analyzed in the frequency range $f = 2–2000$ Hz within which the major portion of oscillation energy fell at a three-percent transmission band and a three-minute time of analysis. From the measurement data we determined the frequencies f_{dis} of the narrow-band components of the spectra of pressure pulsations $L(f)$, their level L_{dis}, the Strouhal numbers $\mathrm{Sh} = f_{\mathrm{dis}} d_{\mathrm{d}}/V$, and the relative depth of the dead end $\bar{t} = tf_{\mathrm{dis}}/a$.

The microphone in experiments in the small wind tunnel was external to the flow, on one side, and at a distance from the baffle. The longitudinal axis of the microphone was perpendicular to the working section axis and placed at a distance of 90 mm downstream from the nozzle exit section. The distance between the microphone screen and the jet axis was 350 mm. In the large wind tunnel, the microphone was placed inside the dead-end cavity at a short distance from its bottom. The results of measurements in the above sections have made it possible to obtain a fairly clear idea about the proceeding processes.

In the small wind tunnel, the pressure pulsations were measured in three cases: in the first, initial case, at the inlet to the dead-end branch and inside of it there were no special structures influencing the flow structure in the nonuniformity; in the second and third cases, at the inlet to the branch and inside of it a grating from five plates of height 60 mm and thickness 0.5 mm and a cellular panel of thickness 25 mm with hexahedral cells were set, respectively. The faces of the latter measured 3 mm and the thickness of the wall was no more than 0.1 mm. In the experiments, we varied the depth, with respect to the baffle surface, of putting the outer and inner free edges of the grating h_{g} and t_{g} and the outer and inner surfaces of the cellular panel $h_{\mathrm{c.p}}$ and $t_{\mathrm{c.p}}$.

Setting a cellular panel of the chosen type in the dead-end mouth leads apparently to some local increase in the hydrodynamical drag of the channel. At the same time, in an incompressible flow with a relatively low velocity such a panel makes it possible, in essence, to prevent the influence on the excitation of self-oscillations of the hydrodynamic structure inside the dead-end cavity preserving the resonator in the oscillatory system.

Results and Discussion. 1. In the small wind tunnel, by measurements of pressure pulsations it has been established, first of all, that their $L(f)$ spectra in the investigated range of flow velocities contain no narrow-band components in the case where the dead-end branch is closed and the baffle surface is smooth and impenetrable. Then the effects caused by the flow around the baffle wall with a nonuniformity were considered.

At minimal experimental Reynolds numbers $(1.7–1.8)\cdot 10^5$ and a ratio $t/d_{\mathrm{d}} = 5.15$ both the grating and the cellular panel in the dead-end mouth make it possible to completely eliminate self-oscillations in the flow characteristic of the initial case, decrease by 10 dB the level of pulsations, and obtain a practically continuous $L(f)$ spectrum. With increasing Reynolds numbers the efficiency of setting a grating in the dead-end branch decreases. At $\mathrm{Re} = 2.46\cdot 10^5$ and $t/d_{\mathrm{d}} = 5.75$ the level of the initial narrow-band component at the frequency $f_{\mathrm{dis}} = 224$ Hz decreases by only 5 dB. But in the case of setting a cellular panel at the inlet to the branch, a continuous spectrum of pressure pulsations is observed in the measurement section, and at the frequency $f = 224$ Hz the L level decreases by 21 dB. A similar picture is also observed at a larger Reynolds number $\mathrm{Re} = 4.05\cdot 10^5$ and at a frequency of initial self-oscillations $f_{\mathrm{dis}} = 700$ Hz when $t/d_{\mathrm{d}} = 1.57$. However, at a larger value of $t/d_{\mathrm{d}} = 3.58$ and the same $\mathrm{Re} = 4.05\cdot 10^5$ the grating is as effective as the cellular panel.

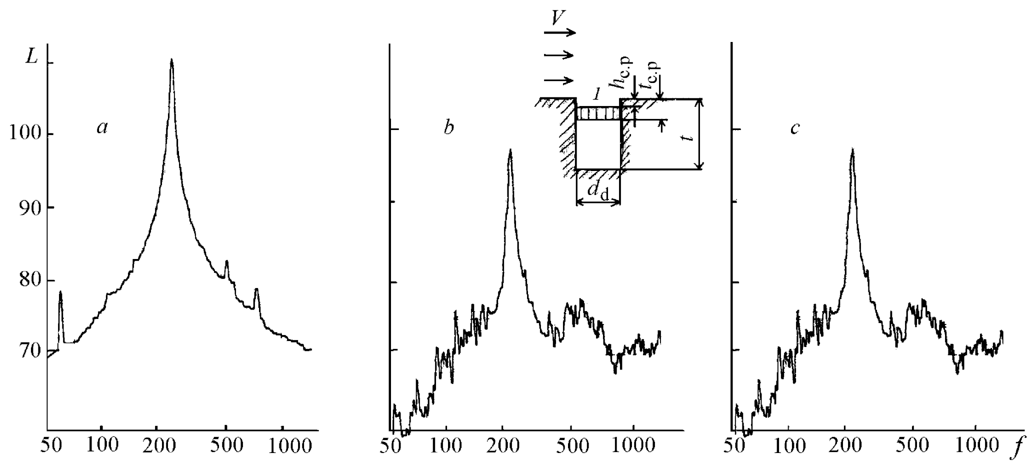

Fig. 1. Spectra of pressure pulsations in the near field of the disturbance source in the small wind tunnel (Re = $4.05 \cdot 10^5$, t/d_d = 5.75): a) with no grating in the niche (Sh = 0.322, $\bar{t}$ = 0.220); b) with a grating from plates in the dead-end branch (Sh = 0.334, $\bar{t}$ = 0.222, h_g = 0, t_g/d_d = 1.13); c) with a cellular panel in the dead end (Sh = 0.324, $\bar{t}$ = 0.215, $h_{c.p}$ = 0, $t_{c.p}/d_d$ = 0.47); 1) cellular panel or grating. L, dB; f, Hz.

In the above experiments, it has been impossible to separate the contribution of the hydrodynamic structures inside and outside of the niche to the formation of self-oscillations in the flow, since the cellular panel in principle can influence the hydrodynamic oscillations not only inside of the dead-end cavity. Nevertheless, the results presented are of interest pointing to the nonmonotonic character of the influence of the grating on large-scale hydrodynamic structures in the zone of the joint of the branch and the baffle surface.

We managed to estimate the role of external and internal hydrodynamic structures in the excitation of self-oscillations at Re = $4.05 \cdot 10^5$ and t/d_d = 5.75. From the spectra given in Fig. 1 it follows that in the case under consideration self-oscillations are excited by the hydrodynamic source outside the dead-end cavity. The level of the narrow-band component of the spectrum of pressure pulsations, as is seen, is markedly decreased by both the grating (by 17 dB) and the cellular panel (by 12 dB). However, self-oscillations persist, and this happens in spite of the fact that the cellular panel in the dead-end mouth, in essence, completely prevents the influence on self-oscillations of any flow inside the cavity. To dispel doubts on this score, we set cellular panels simultaneously not only in the mouth of the dead-end branch, but also inside of it, filling almost the whole of the cavity space with cells, and this did not lead to a damping of self-oscillations in the flow.

In the near-wall flow on the baffle, a laminar-turbulent transition characterized by the formation of large-scale coherent hydrodynamic structures takes place. Apparently, only these latter structures in the considered experiment can be a source of narrow-band acoustic radiation exciting the cavity-resonator. It is clear that the relative depth of the dead end $\bar{t}$ therewith should be somewhat smaller than a quarter of the acoustic wave length, as was just observed in practice (Fig. 1).

To verify the foregoing, we turned to the experiment performed in [9], in which the excitation of self-oscillations in the flow past a wing with an extensive transition region extending to the trailing edge of the downstream face of its airfoil was studied. It was shown in [9] that the introduction of even a small disturbance from the thermoprobe legs into the laminar-turbulent transition region with its large-scale formations led to an abrupt and almost complete cessation of self-oscillations. A similar experiment and with the same result has also been carried out in the present work. It should be noted that in [9] the ability of the transition to generate narrow-band noise was not emphasized.

2. In the large wind tunnel T-5 measurements were made in four cases. In the first case, the niche mouth was closed with a smooth impenetrable panel. In the second case, the cavity mouth was open and contained no elements acting on the flow. In the third and fourth cases, in the mouth of the dead-end branch a grating from plates and a thin perforated panel were set, respectively. The measurement data on pressure pulsations in the near field of the free jet and the velocity in the boundary layer on the wall and in the flow core inside the nozzle, as well as in the open

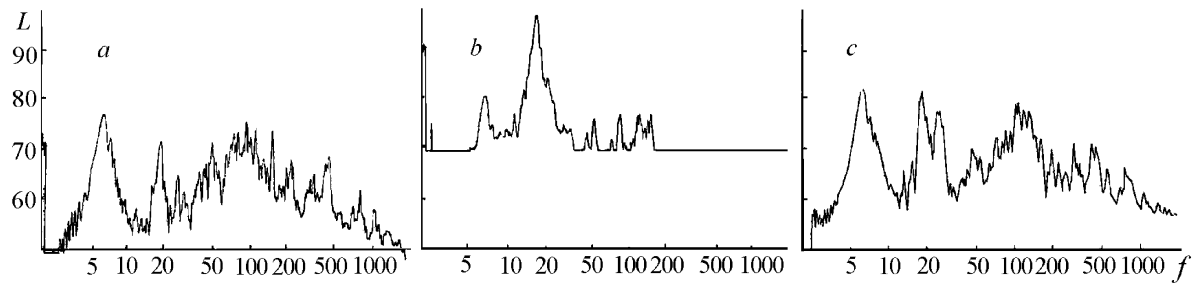

Fig. 2. Spectra of pressure pulsations near the bottom of the dead-end cavity: a) the inlet into the dead-end branch is closed with an impenetrable panel; b) the inlet into the niche is completely open (Sh = 0.519); c) the inlet into the dead end is closed with a perforated panel (Sh = 0.566). L, dB; f, Hz.

working section of the wind tunnel T-5 when it had no baffle model, are presented in [10]. According to the data of [10], typical of the T-5 tunnel in the range of Reynolds numbers $(1.3–3.6)\cdot 10^6$ are regimes of low-frequency self-oscillations with coupled hydrodynamic and acoustic disturbances with a large azimuth correlation of hydrodynamic pulsations in the near-wall flow inside the nozzle and immediately upon leaving it in the free jet. This told on the spectra of pressure pulsations inside the branch recorded upon closing its inlet with an impenetrable panel (Fig. 2a, Re = $2.17\cdot 10^6$).

When the niche was completely open, in the zone of the baffle-branch joint the flow topology changed, the scales of hydrodynamic formations and the L_{dis} level of the narrow band noise generated by them at frequencies $f_{dis} \approx 17.4–21$ Hz and, to a lesser extent, at 6.3–6.7 Hz (sometimes at 10 Hz) increased. The above nonuniformity in the flow became a kind of amplifier of low-frequency oscillations. The acoustic radiation was amplified by the resonant space between the inlet (near the floor) to the dead-end cavity and the ceiling over the open working section of the T-5 tunnel. According to estimates, it was this space, and not the dead-end niche, that became in the given experiments a resonator of the narrow-band signal in the range f_{dis} = 17.4–21 Hz and an element of the self-sustained-oscillation system. Obviously, the above-mentioned fact does not change the basic mechanism of the self-oscillations being analyzed. In the pulsation processes under consideration, the acoustic radiation realizes a feedback amplifying the initial hydrodynamic disturbances.

As a result, at Reynolds numbers $\mathrm{Re}\cdot 10^{-6}$ = 1.48, 2.17, 2.92, 3.46, and 4.35 in the measurement section the level of narrow-band pressure pulsations at frequencies 17.4–21 Hz reached 96–115 dB (Fig. 2b, Re = $2.17\cdot 10^6$), while with a closed mouth it did not exceed 72 dB. It should be noted that the smaller values (6.3–10 Hz) correspond to the first harmonic of wave disturbances [11] in the turbulent boundary layer on the tunnel nozzle wall, and the larger ones (17.4–21 Hz), to the second or third mode. The slight spread of the frequencies under consideration is due to the instability of the self-oscillation regimes in the wind tunnel [10], which was also observed in our experiments.

The application of a grating from plates for changing the pressure pulsation field turned out to be ineffective. But when in the mouth of the dead-end cavity a perforated panel was set, then the levels of self-oscillations in the measurement section became much lower — by 13–26 dB (Fig. 2c, Re = $2.15\cdot 10^6$), and at Re = $4.35\cdot 10^{-6}$ self-oscillations ceased. It may be suggested that in the last case, though at smaller Reynolds numbers as well, the perforated panel brought to naught the role of the large-scale hydrodynamic structures inside the niche in the formation of the self-oscillatory system. But there were no external disturbances at Re = $4.35\cdot 10^6$ in the flow, and large-scale disturbances in the joint zone ceased. At the other Reynolds numbers given above such disturbances existed by virtue of the above-mentioned features of the wind tunnel, and the perforated panel could not completely prevent self-oscillations in the considered region of the flow.

It should be noted that at $\mathrm{Re}\cdot 10^6$ = 5.1 and 5.8 self-oscillations in the wind tunnel were not excited; neither were they observed in the region of the inlet to the niche when it was open, unlike the case with Re = $4.35\cdot 10^6$.

3. Apparently, setting the cellular panel at the same level with the surface over which air passes and setting the grating from plates so that it extended beyond its boundaries, we proceeded from the hypothetical notion that precisely such their arrangement in the niche is optimal for effective action on the external and internal large-scale hydrodynamic structures. As a result of the investigations in the small wind tunnel, it has been found that there is also

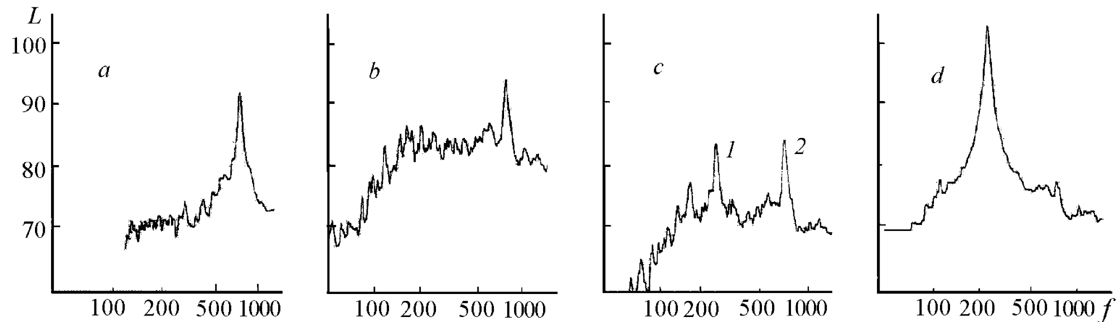

Fig. 3. Spectra of pressure pulsations in the near field of the perturbance source in the small wind tunnel (Re = $3.86 \cdot 10^5$, t/d_d = 5.75): a) inside the dead-end branch a grating from plates is present (Sh = 1.013, $\bar{t}_g$ = 0.181, t_g/d_d = 1.53); b) inside the dead end a cellular panel is present (Sh = 1.038, $\bar{t}_{c.p}$ = 0.19, $t_{c.p}/d_d$ = 1.57); c) inside the cavity a cellular panel is present (Sh_1 = 0.334, $\bar{t}$ = 0.225, Sh_2 = 0.967, $\bar{t}_{c.p}$ = 0.290, $t_{c.p}/d_d$ = 2.57); d) inside the niche a cellular panel is present (Sh = 0.328, $\bar{t}$ = 0.221, $t_{c.p}/d_d$ = 4.72). L, dB; f, Hz.

another way of damping intensive self-oscillations when a grating from plates or a cellular panel are placed at a certain depth inside the dead-end cavity. In the considered range of values of t_g/d_d and $t_{c.p}/d_d$ (Fig. 1(1)), the shift of self-oscillations to the third-harmonic frequency of initial disturbances was observed (Fig. 3a, b and Fig. 1a). We also observed the formation of a spectra of pressure pulsations with two intensive narrow-band components at the above-mentioned frequencies (Fig. 3c) and a lowering of the L_{dis} level by 16–25 dB.

As follows from the results presented, the observed transformation of the spectra results from the reflection of weak acoustic initial disturbances at the frequency f_{dis} = 725 Hz by the gratings of both considered types. In this part of the investigation, we did not aim at optimizing the structure of the gratings and the depth of their location in the niche for damping the self-oscillations most effectively. Judging from the results, this method for damping self-oscillations shows promise.

CONCLUSIONS

1. Narrow-band acoustic radiation is generated by large-scale wave disturbances in the transition and turbulent boundary layer and becomes highly manifest in the presence of a dead-end cavity-resonator.

2. The grating placed inside the dead-end channel may become a baffler of acoustic disturbances. The reflection by the grating of sound disturbances in the dead-end cavity at the third-harmonic frequency of initial self-oscillations leads to a significant damping of the latter and even to their frequency shift.

3. Apparently, precisely the presence of coupled acoustic and hydrodynamic oscillations in coherent large-structures in the transition and turbulent boundary layer permits acting on its development by acoustic radiation.

NOTATION

a, velocity of sound in the gas, m/sec; d_n, diameter of the wind tunnel nozzle, m; d_d, inner diameter of the dead-end branch, m; f, pressure pulsation frequency, Hz; L, level of pressure pulsations in the near field of the disturbance source, dB; h, depth of immersion of the grating into the cavity, m; p, pulsation component of the instantaneous value of the pressure, Pa; Re = Vd_n/ν, Reynolds number characterizing the flow at the outlet from the nozzle of the wind tunnel; Sh = $f_{dis}d_d/\nu$, Strouhal number; t, depth of the cavity-resonator, m; $\bar{t} = tf_{dis}/a$, relative depth of the resonator niche; $t_g(t_{c.p})$, depth of immersion into the dead-end branch of the grating from plates (cellular panel) measured from the surface of the inlet to the dead end to the edge of the plates (cellular panel) most distant from it; $\bar{t}_g = t_g f_{dis}/a(\bar{t}_{c.p} = t_{c.p}f_{dis}/a)$, relative depth of immersion of plates (cellular panel) calculated from the frequency of reflection from the grating of narrow-band acoustic disturbances; V, undisturbed flow velocity at the outlet from the nozzle, m/sec; ν, kinematic viscosity coefficient, m^2/sec. Subscripts: dis, disturbance; g, grating from plates; n, nozzle; c.p, cellular panel; d, dead end.

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