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GENERATION OF INTENSIVE NARROW-BAND DISTURBANCES IN A FLOW WITH A LARGE-SCALE HYDRODYNAMIC STRUCTURE

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This paper analyzes the reasons for the appearance of intensive narrow-band disturbances and self-sustained oscillations in a flow with an inhomogeneity on its boundary. It has been shown that self-sustained oscillations are due to the formation of large-scale cocurrent hydrodynamic systems with vortex structures and acoustic feedback. It is supposed that the vortex formed in the zone near the edge of the surface generates noise as a result of the involvement in the rotary motion of the azimuth-inhomogeneous structure. It is noted that self-sustained oscillations can be avoided or suppressed by disorganizing the elements of the large-scale hydrodynamic structure.

Introduction. The problem of the generation in vortex-structure flows of intensive narrow-band pressure pulsation arose, as is known, in those cases where in the path or on the aerodynamic surface there were inhomogeneities of different types, for example, niches on the wall or an open working section in a wind tunnel, or finally the trailing edge of the airfoil section. It should be noted that in some cases the intensive narrow-band pressure pulsations were essentially hydrodynamic disturbances and did not propagate far from its source — the vortex. In other situations, the narrow-band component of the spectra of pressure pulsations contained an acoustic model of a high level realizing feedback for the self-sustained oscillation system formed in the flow. Noteworthily, acoustic vibrations are more dangerous than hydrodynamic ones because they propagate for a long distance from their source in the flow field, for example, in a pipeline.

The level of the considered pressure pulsations is such that in some cases industrial constructions, e.g., bindings of manifold gas compressor plants, are endangered, and in other cases the flow-generated sound becomes inadmissible for different reasons.

Naturally, avoiding or at least attenuating dangerous pressure pulsations required the formation of certain ideas about how these narrow-band disturbances become possible. Such ideas for different situations were formed, in particular, in [1–5], and their comparison seemed to have revealed certain inconsistencies.

The aim of the present work was to compare and analyze the physical models [1–5] and the already existing highly extensive experiments and find models of the processes under considerations that are compatible with the latter and with one another. The data used by us from the investigations published at different times are supposed to be indispensable and sufficient, in the main, for the above analysis.

Here we consider three cases of excitation by vortex structures of intensive narrow-band pressure pulsations in a flow and outside of it. In so doing, the self-sustained oscillation system whose elements become vortex formations becomes complicated from the first to the third situations.

1. Flow Past a Wing. In [6, 7], the question of what accompanies the generation of intensive narrow-band noise in flowing past a straight wing installed in a wind tunnel in an acoustic chamber at a small angle of attack $\alpha = 5^o$ was investigated. It was established by measurements that intensive sound radiation arises under certain flow conditions of the model and correlates fairly reliably with velocity pulsations in the boundary layer of the wing and in the wake behind it. The results of these measurements of noise in the near field of the source of hydrodynamic disturbances and velocity pulsations in the boundary layer and in the wake are presented in Figs. 1–4 [6].

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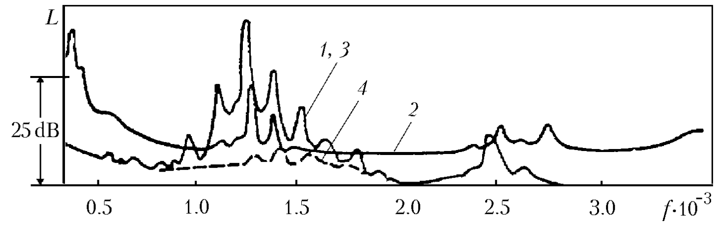

Fig. 1. Spectra of noise in the near field in the airfoil flow ($\alpha = 5^{\circ}$, Re = $3.5 \cdot 10^5$): 1) hydraulically smooth surface; 2, 3) three bumps on the upstream and downstream faces, respectively; $\bar{x}_r = 0.086$; 4) turbulence stimulator on the downstream face, $\bar{x}_{tr} = 0.485$. L, dB; f, Hz.

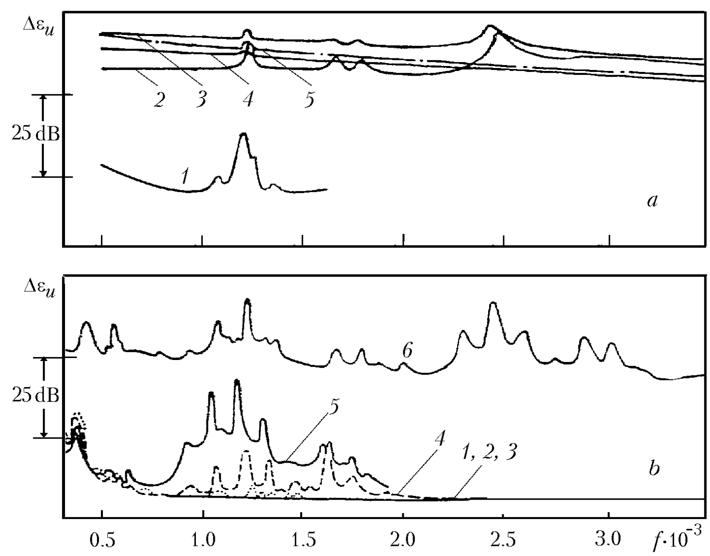

Fig. 2. Spectra of velocity pulsations in the boundary layer ($\alpha = 5^{\circ}$, Re = $3.5 \cdot 10^5$): a) upstream face, $y \approx 0.5$ mm [1) $\bar{x} = 0.28$, 2) 0.36, 3) 0.474, 5) 0.971]; b) downstream face, $y \approx 0.2$ mm [1) $\bar{x} = 0.086$, 2) 0.308, 3) 0.554, 4) 0.77, 5) 0.87, 6) 0.97]. f, Hz.

From the experimental data presented in [6] it was concluded that an intense tonal noise, essentially similar to the noise of a rotating blade system, is possible as a result of the formation of a self-sustained oscillation system in flowing past the model. Precisely the hydrodynamic waves of the Tollmin–Schlichting instability with a characteristic frequency packet in the extensive zone of transition from laminar to turbulent flow conditions in the boundary layer on the downstream face of the airfoil move into the wake behind the wing and predetermine the development of vortex structures and the generation of narrow-band acoustic disturbances. The high level of the latter is due to the fact that both the waves and the vortices are large-scale coherent hydrodynamic formations.

The upstream acoustic radiation realizes feedback on the discontinuity, the nose of the wing, generates or intensifies the already existing in the flow hydrodynamic disturbances of the same frequency as the waves in the transient flow, and increases their amplitude. Accordingly, the level of pressure pulsations of the acoustic mode also increases. The testing actions on the turbulent boundary layer on the upstream face of the model airfoil practically did not influence the intensity of pressure pulsations in the near field (see Fig. 1), whereas placing a vortex generator on the downstream face of the airfoil completely prevented narrow-band sound radiation.

It should be noted that in the experiments performed in [6, 7] downstream behind the wing there were not any surfaces the interaction of vortices with which could cause narrow-band sound radiation.

The results of the investigations of [6, 7] did not permit determining how the spanwise extending large-scale hydrodynamic structures initiate tonal noise. The missing data for constructing a hypothetical model can probably be

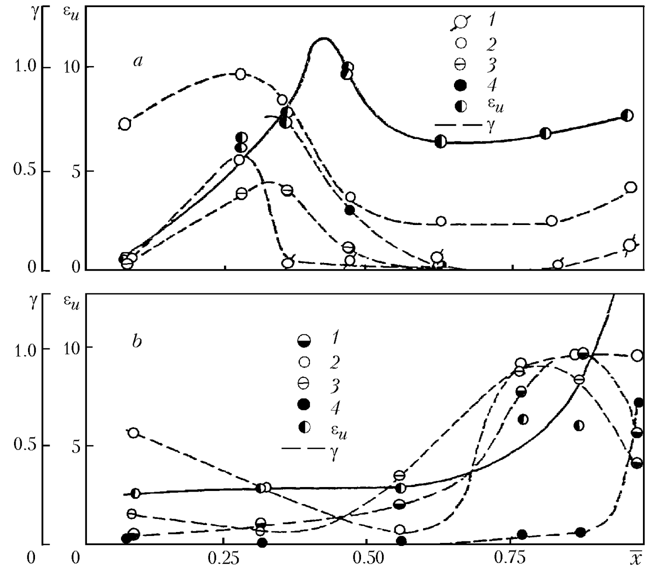

Fig. 3. Change in the coherence coefficient γ and pulsation intensity of velocity ε_u along the length of the airfoil chord (α = 5$^{\rm o}$, Re = 3.5·10^5): a) upstream face, $y \approx 0.5$ mm [1) $f_{\rm d}$ = 1080–1090 Hz; 2) 1210–1248; 3) 1345–1380; 4) 2500–2510]; b) downstream face, $y \approx 0.2$ mm [1) $f_{\rm d}$ = 1060–1100, 2) 1190–1272, 3) 1320–1360, 4) 2490–2500]. ε_u, %; $\bar{x}$, m.

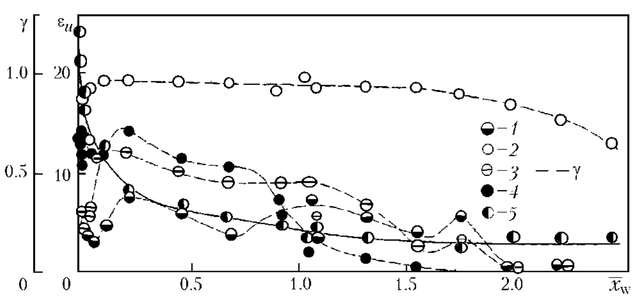

Fig. 4. Change in the coherence coefficient γ and pulsation intensity of velocity ε_u along the coordinate $\bar{x}_{\rm w}$ in the wake behind the airfoil (α = 5$^{\rm o}$, Re = 3.5·10^5): 1) $f_{\rm d}$ = 1090–1100 Hz; 2) 1220–1230; 3) 1370–1390; 4) 2460–2484; 5) ε_u. ε_u, %; $\bar{x}_{\rm w}$, m.

taken from the visual observations [5] of the structure of the single ring vortex formed behind the nozzle exit section of a pulsed wind tunnel and moving in a medium at rest (Fig. 5).

From the experiments of [5, 8, 9] it follows that a single two-dimensional vortex has a laminar core, a region of transient flow conditions, and a turbulent periphery. As is known, it is in the regions of transient flow conditions that large-scale vibrations of a high level arise.

It is reasonable to conclude that also when the boundary layer — turbulent from the upstream and transient from the downstream face of the airfoil — sheds from a straight wing and rolls into a spanwise extending vortex the structure of the latter in the cross-section is apparently the same as in the single ring vortex shedding from the nozzle exit section [5]. The large-scale ring vortex at the exit from the nozzle arises, as is known, as a result of the instability of the shear flow, *primary* in the case under consideration (Fig. 5). And the waves observed in the vortex are a consequence of the *secondary* instability of the flow in the vortex structure itself. It should be noted that the waves of the secondary instability and the waves completing their development have a smaller scale than the vortex generated by the primary instability, and turn out to be involved in the rotatory motion.

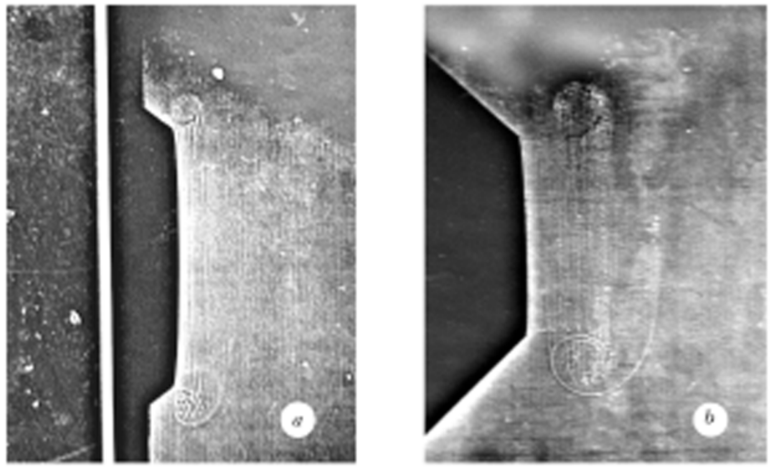

Fig. 5. Vortex near the nozzle exit section of the pulsed wind tunnel (a) and at a short distance from the section (b).

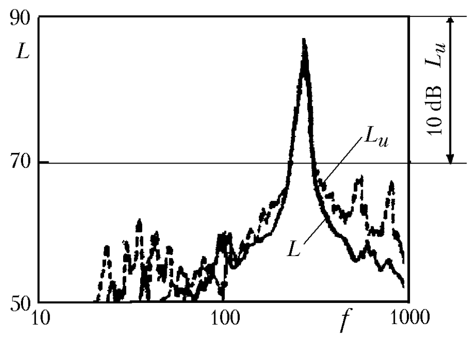

Fig. 6. Spectra of pressure pulsations $L(f)$ in the near field and velocity pulsations $L_u(f)$, $x_1 = 0.302$, $y_1 = 0.0189$, $z_1 = 0$. L, dB; f, Hz.

Likewise, large-scale waves of the *primary* instability developing upstream on the downstream face of the airfoil and predetermining, apparently, vibrations in the zone of transient flow condition, and, perhaps, on the flow periphery, get involved in the rotary motion in the vortex behind the wing [6]. It seems that precisely such a structure of the vortex motion in the wake immediately after the wing is responsible for the generation of tonal noise reaching a high level [6, 7] as a result of the formation of a self-sustained oscillation system in flowing past the model in the narrow frequency bands.

It should be noted that by virtue of the features of the experimental technique, measurements [3–5] of noise of the single ring vortex could only be made in that period of its development when the structure of the vortex noticeably differed from its initial structure (Fig. 5). In so doing, practically no jet flow was observed, the zone of transient flow conditions was markedly smeared, and the narrow-band noise measured in the experiments could have also been due to the vibrations deforming the laminar core of the vortex.

2. Flow Past a Surface with a Niche. As can easily be seen, the two-dimensional flow past a surface with a niche is definitely similar to that considered in Section 1. Indeed, in many practical problems, the leading edge of the junction of an aerodynamic surface with a niche is approached by a turbulent flow, most often without regular large-scale vibrations. This is a plain analog of the flow on the upstream face of the airfoil [6]. A vortex [10] with all its vibrations directed from the bottom of the niche to the leading edge of its junction with the surface of the body flows past the front downstream interior wall of the niche near its inlet. Thus, in principle, the flow approaches the leading edge of the junction from which a stall into the niche occurs in the same manner as it approaches the trailing edge of the wing. And the length of the downstream path on which a wake develops behind the leading edge of the junction, as opposed to [6], is bounded by the downstream wall of the niche.

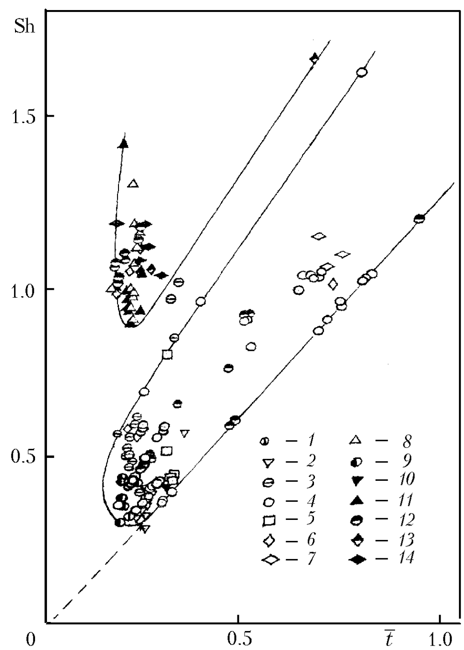

Fig. 7. Strouhal number Sh of self-sustained oscillations in pipes with one dead branch versus the length of the dead part $\bar{t}$: $\mathrm{Re}_c \cdot 10^{-5} \geq 1.5$, $t/d_{de} \geq 2.6$ [1) d_{de}/d_c = 0.179, 2) 0.276, 3) 0.355, 4) 0. 468, 5) 0.7 (tests at the gas compressor station), 6) 0.733, 7) 0.853]; $\mathrm{Re}_c \cdot 10^{-5} < 1.5$, $t/d_{de} > 2.6$ [8) d_{de}/d_c = 0.353]; $\mathrm{Re}_c \cdot 10^{-5} > 1.5$, $t/d_{de} \leq 2.6$ [9) d_{de}/d_c = 0.179, 10) 0.276, 11) 0.353, 12) 0.468, 13) 0.733, 14) 0.853].

Vibrations in the wake behind the front edge of the niche can be initiated by both disturbances in the flow before the niche and pulsations emitting from the zone of transient flow conditions inside the vortex. Here it is assumed that the structure of the vortex in its cross-section behind the front edge of the niche does not differ appreciably from that considered above.

It is assumed that the rotation in the transition and external regions of the vortex of large-scale disturbances with a high-level amplitude leads, in flowing past a wing [6], to the radiation of tonal noise. The latter is amplified by the niche-resonator and can realize feedback due to the formation of a self-sustained oscillation system enhancing the hydrodynamic disturbances on the leading edge of the junction between the niche and the aerodynamic surface.

In [2], it is pointed out that the tonal noise in the considered situation is generated not by the vortex flow in the niche, but results from the interaction of hydrodynamic instability waves in the shear flow behind the leading edge of the junction with its downstream edge. Getting somewhat ahead, it should be noted that in [11] and [12] the interaction between the rather intensive vortex disturbances and the edge of the diffuser of a wind tunnel with an open working section and with the outlet section of the check valve of the manifold gas-compressor plant was considered. A change in the shape and rigidity of the diffuser edges and the valve outlet did not lead to a marked change in the parameters of self-sustained oscillations.

In the majority of practical problems, as opposed to the foregoing, the flow in the region of the junction between the niche and the aerodynamic surface is spatial in nature. Nevertheless, as we see it, also in this situation the fundamental structure of the flow in the niche is similar to that realized in the case of the two-dimensional flow. In particular, the intensive narrow-band velocity pulsations observed in [13] in a pipe-collector with a blind branch at its inlet in the regimes of self-sustained oscillations can reasonably be regarded as evidence of the existence of instability waves in the zone of the flow in the transition regime and a turbulent periphery of the vortex in the niche. The correspondence between the frequencies of intensive narrow-band pressure pulsations in the near field and velocity pulsations in the flow itself leaves no doubt about the interrelationship between acoustic and hydrodynamic disturbances generated by the flow in the region of the inlet to the blind branch (Fig. 6).

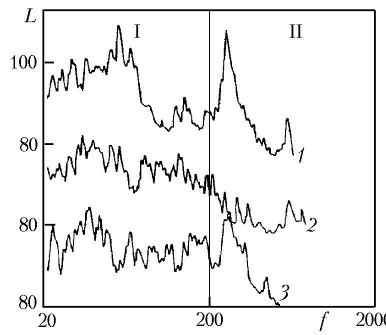

Fig. 8. Spectra of pressure pulsations on the wall of the collector with a branch at $d_{\mathrm{de}}/d_{\mathrm{c}}$ = 0.733: 1) t_{c1} = 4.6; $\mathrm{Sh}_{\mathrm{cI}}$ = 0.406, ε_p = 2.17% and $\mathrm{Sh}_{\mathrm{cII}}$ = 1.81, ε_p = 1.73%; 2) t_{c1} = 2.57; 3) t_{c1} = 1.19, $\mathrm{Sh}_{\mathrm{cI}}$ = 0.26, ε_p = 1.15% and $\mathrm{Sh}_{\mathrm{cII}}$ = 1.81, ε_p = 0.99%. L, dB; f, Hz.

It should be noted that the assumption of the fundamental similarity of vortices in the two-dimensional and spatial niches was used as the basis for effective use of lattices of longitudinal partitions in the blind branch to prevent or weaken the generation of disturbances in the flow inside the collector [13]. It was assumed that as in the hypothetic two-dimensional vortex, these plates oriented along the main stream would lessen the scales of the coherent structures responsible for the tonal noise radiation, disorganize them, and influence the very development of instability waves, as was in the case of the flow past a straight wing with low longitudinal ribs installed on its surface. In many situations, such an approach, natural in the case of the two-dimensional vortex, proved to be also useful in the case of the spatial character of the vortex structure.

We have considered the above situations where in the flow a self-sustained oscillation system with a vortex structure — the source of hydrodynamic disturbances and intensive generation of narrow-band noise — was formed. In [14], it has been shown that for such a self-sustained oscillation system containing a resonator (niche, channel of closed a wind tunnel) the region of acoustic instability in the plane of parameters Sh–t can be indicated (Fig. 7).

In regimes characterized by Strouhal numbers Sh and relative length t belonging to the above-mentioned region, related hydrodynamic and acoustic components of the spectra of pressure pulsations that stand out sharply against the general background are realized. As opposed to this, in regimes with parameters lying outside the region of acoustic instability, as is shown in [15], the unstable vortex structure in the niche initiates only intensive hydrodynamic oscillations in a limited region of the flow (Fig. 8). In so doing, no narrow-band noise standing out against the continuous spectrum in measurements in the near field is observed. Finally, in [15] it has been established that at certain geometrical ratios in the niche, stable vortex structures exciting no hydrodynamic and acoustic pressure pulsations standing out against the continuous spectrum are realized.

3. Self-Sustained Oscillation System in a Wind Tunnel. In closed wind tunnels with an open working section, vortex structures, as in the above cases, play a key role in the appearance of self-sustained oscillations with a characteristic high level of intensity of velocity pulsations ε_u in a part of the path and pressure pulsations ε_p in the flow and outside of it (Fig. 9, Re = $V_\infty d_{\mathrm{n}}/\nu$, [11]). The structure of the circular vortices around the free jets formed behind the nozzle exit section and generating tonal narrow-band noise has been considered above (see Fig. 5a).

However, as was shown in [11], the boundary layer shedding from the nozzle walls into the open working section of he wind tunnel, unlike that observed in [5], already contains intensive hydrodynamic oscillations of the same frequency as the tonal noise standing out against stochastic pulsations and predetermining the frequency of self-sustained oscillations in the tunnel along with the resonance response of the path. In particular, in the experiments of [11], waves of primary instability of the boundary layer involved, due to its rolling in the open working section, in the rotation of large-scale vortices move downstream to the nozzle exit section of a small wind tunnel.

In the regimes of self-sustained oscillations, the acoustic radiation, as in the previously considered cases, plays the role of a feedback increasing the amplitude of hydrodynamic waves in the narrow frequency band inside the nozzle and at its exit. In so doing, the tunnel path itself acts as both a fiber and a resonator.

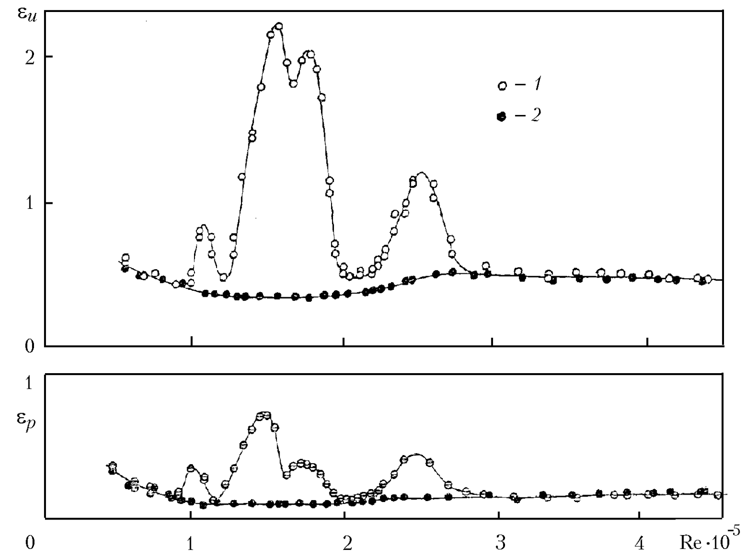

Fig. 9. Intensity of velocity and pressure pulsations ε_u and ε_p versus the Reynolds number (d_n = 150 mm, open working section, ε_u at x = 105 m, r = 0, ε_{p1} at x = 30 m, r = 187 mm in the horizontal symmetry plane of the jet): 1) initial variant; 2) cellular panel at the inlet to the circular funnel of the diffuser. ε_u, %.

A distinguishing feature of the considered self-sustained oscillation system is the presence in the flow of plane hydrodynamic waves in a portion of the tunnel path propagating downstream behind the nozzle entrance and ending at the diffuser end. According to the mathematical model of [16], the presence in the flow of periodic large-scale coherent structures leads to the appearance in it of an acoustic vibrational mode. Earlier this fact was actually negated in [1].

Thus, intensive tonal noise in the wind tunnel in self-sustained oscillation regimes is generated by vortices both in the open working section and in the flow inside a part of the path. Disorganization of the coherent structures before the diffuser inlet performed in [11] made it possible to practically prevent self-sustained oscillations. The authors of [11] were unable to verify the hypothetical assumption that sound was generated by the interaction between the vortices around a free jet and the inlet edge of the diffuser, as mentioned above.

Noteworthy is the fact that in the cases where the self-sustained oscillation system is not realized, it has been impossible to separate the tonal noise of vortices against the background of the continuous spectrum of the flow noise in all the cases considered in Sections 1–3.

CONCLUSIONS

1. The tonal noise radiation by a vortex is likely due to the involvement in the rotational motion in the vortex of the wave structures and the small-scale vortex formations completing their development.

2. In most cases, the vortex structures by themselves generate low-level tonal noise.

3. The maximum intensity of tonal noise is reached when in the flow a large-scale coherent hydrodynamic structure is formed, whose elements, apart from vortices, are also wave disturbances existing upstream and downstream of them.

4. Acting on individual elements of a large-scale hydrodynamic structure, it is possible to prevent the formation of a self-sustained oscillation system in the flow or markedly decrease the oscillation amplitude of the pressure and velocity.

NOTATION

a, velocity of sound in the gas, m/sec; b, chord of the wing model, m; d_n, nozzle diameter of the wind channel, m; d_c and d_{de}, internal diameters of the collector pipe and dead branch, respectively, m; f, pulsation frequency of pressure and velocity, Hz; L, pulsation level of the pressure at the control point of the near field, dB; L_u, pulsation of the longitudinal velocity component, dB; r, radial coordinate of measurements counted off from the axis of the open working section of the wind tunnel, m; Re and $\mathrm{Re_c}$, Reynolds numbers characterizing the flow past the wing model ($\mathrm{Re} = V_\infty b/\nu$), flow in the open working section of the wind tunnel ($\mathrm{Re} = V_\infty d_\mathrm{n}/\nu$), and flow in the pipe-collector ($\mathrm{Re_c} = V_\infty d_\mathrm{c}/\nu$); $\mathrm{Sh} = f_\mathrm{d} d_\mathrm{de}/V$, Strouhal number; $\mathrm{Sh_c} = f_\mathrm{d} d_\mathrm{c}/V$; t, length of the resonant part in the path at the site of the dead branch, m; $\bar{t} = t f_\mathrm{d}/a$, relative depth of the dead branch; t_c, depth of the dead branch in the pipe-collector, m; $t_1 = t/d_\mathrm{de}$, dimensionless depth of the dead branch; $t_{\mathrm{c}1} = t_\mathrm{c}/d_\mathrm{c}$; u, longitudinal velocity component in the boundary layer or wake, m/sec; V_∞, velocity of the undisturbed flow incident on the wing model, m/sec; V, mean-flow-rate velocity in the pipe-collector, m/sec; x, distance to the observation section from the wing nose measured along the model chord (Section 1), from the front downstream point of the junction of two pipes along the element of the pipe-collector (Section 2) and from the nozzle exit section along its axis (Section 3), m; $\bar{x} = x/b$; $x_1 = x/d_\mathrm{de}$; x_w, distance along the axis parallel to the velocity vector V_∞ from the rear edge of the wing to the section of measurements in the wake, m; $\bar{x}_\mathrm{w} = x_\mathrm{w}/b$; x_r and x_tr, longitudinal coordinate of setting on the wing surface of roughness and turbulence stimulator, m; $\bar{x}_\mathrm{r} = x_\mathrm{r}/b$; $\bar{x}_\mathrm{tr} = x_\mathrm{tr}/b$; y, distance from the thermonozzle filament to the wing surface along the normal to it (Section 1) and to the pipe-collector element along the normal to it (Section 2), m; $y_1 = y/d_\mathrm{de}$; z, coordinate of the measurement section normal to x and y in the right coordinate system, $z_1 = z/d_\mathrm{de}$; α, angle of attack, deg; γ, coherence coefficient of velocity pulsations in the boundary layer or wake and pressure pulsations at the control point of the near field; ε_u and ε_p, intensity of pulsations of the longitudinal velocity component and pressure, respectively, %; ν, kinematic viscosity coefficient of the gas, $\mathrm{m^2/sec}$. Subscripts: 1, dimensionless quantity; d, disturbance; c, collector; n, nozzle; w, wake; de, dead branch; tr, turbulence stimulator; r, roughness.

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