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EFFECT OF THE MODE OF FLOW IN THE INITIAL BOUNDARY LAYER ON THE TURBULENCE ATTENUATION EFFECT IN A JET EXPOSED TO ACOUSTIC IRRADIATION

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Based on an analysis of experimental data on high-frequency acoustic excitation of turbulent jets, we investigate the effect of the mode of flow in the boundary layer of the outlet section of the nozzle on realization of the turbulence attenuation effect. It is claimed that high-frequency acoustic excitation of jets leads to a decrease in turbulent fluctuations on the axis of the initial stretch of the jet and to reduction of noise in both initially laminar and initially turbulent boundary layers at the nozzle outlet.

Investigations of acoustic irradiation of a turbulent jet revealed two effects: low-frequency acoustic excitation (longitudinal or transverse) enhances mixing, while high-frequency acoustic irradiation attenuates it. In the first case the noise of the jet in the near and far fields is increased, while in the second case it is decreased [1, 2].

Low-frequency excitation occurs at the frequency f of large-scale periodic structures at the end of the starting length of a nonirradiated jet. The Strouhal number $\mathrm{St}_d = fd/u_0 = 0.2-0.5$ corresponds to this frequency. The frequency f of fine-scale periodic structures in the mixing layer near the exit section of the nozzle corresponds to high-frequency excitation. The Strouhal number based on this frequency is $\mathrm{St}_d = fd/u_0 = 2-5$. Sometimes the Strouhal number is determined from the momentum thickness θ_0 in the initial section of the boundary layer: $\mathrm{St}_\theta = f\theta_0/u_0$; when $\theta_0/d = 0.01$, we obtain $\mathrm{St}_\theta = 0.02-0.05$.

It is shown in a number of experiments that both effects are realized in both an initially laminar and turbulent boundary layer in the exit section of a nozzle [3]. However, in some experiments the turbulence attenuation effect in the case of high-frequency acoustic irradiation could be realized only in an initially laminar boundary layer [4]. In [5] the indicated effect was obtained for a jet with initially laminar and turbulent boundary layers, and in [6] also with initially laminar and turbulent boundary layers, but in the latter case the turbulence was barely noticeable.

Analysis of the available experimental results on acoustic irradiation of turbulent jets is hindered by the fact that in many of the tests the initial conditions of discharge and, correspondingly, the mode of boundary-layer flow were not controlled.

We will consider results of experimental investigations of high-frequency acoustic excitation of a turbulent jet with controlled initial conditions of discharge. In this case the turbulence attenuation effect was indicated by an increase in the mean velocity or a decrease in the velocity fluctuations on the jet axis, or by a decrease in the noise of the jet in the near and far acoustic fields.

As follows from the dependences of the mean velocity on the jet axis u and the root-mean-square fluctuations of the longitudinal velocity u' on x/d in the absence and presence of longitudinal acoustic irradiation (Fig. 1), the irradiation effect is most pronounced at $x/d = 8-9$ and is much less perceptible at $x/d = 2$. Therefore, the conclusions of [4] that were based on a comparison of velocity fluctuations in the presence and absence of high-frequency acoustic irradiation in the section $x/d = 2$ seem to us to be insufficiently convincing.

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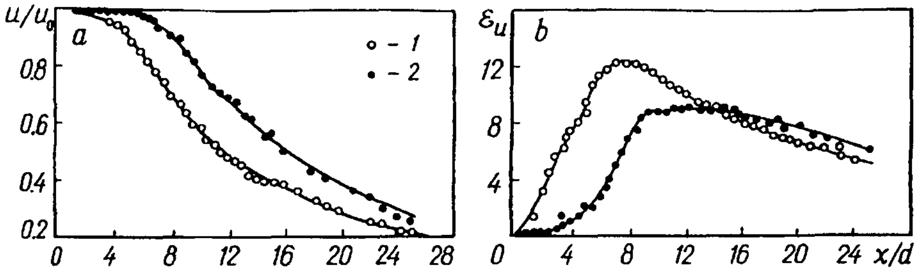

Fig. 1. Change in the mean velocity (a) and longitudinal fluctuations of velocity (b) along the jet axis in the absence (1) and presence (2) of acoustic excitation at $\mathrm{St}_d = 2.75$. ε_u, %.

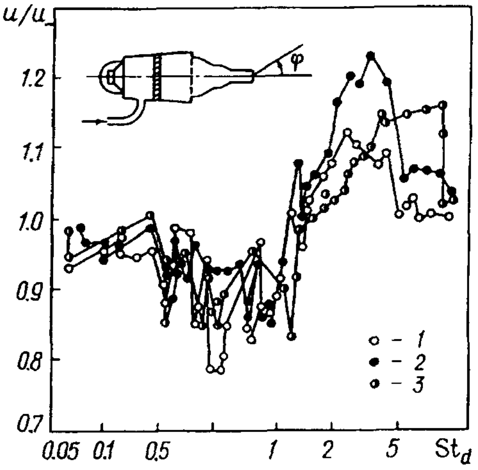

Fig. 2. Change in the mean velocity on the jet axis at the point $x/d = 8$ as a function of the Strouhal number of the longitudinal acoustic irradiation for different values of the form parameter of the boundary layer: 1) $H = 2.59$, 2) 2.35, 3) 1.52.

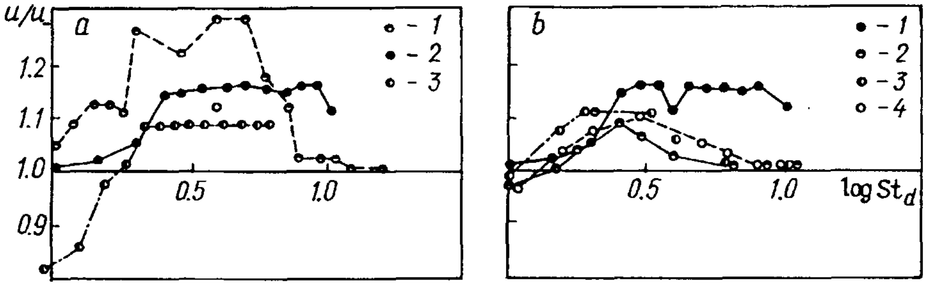

Fig. 3. Change in the mean velocity on the jet axis at the point $x/d = 8$ as a function of the Strouhal number of transverse acoustic irradiation: a) $L = 136$ dB, 1) $u_0 = 10$ m/sec, 2) = 20, 3) 32; b) $u_0 = 20$ m/sec, 1) $L = 136$ dB, 2) 124, 3) 119, 4) 113.

Figure 2 presents results of an experimental investigation [3] of longitudinal acoustic irradiation of a turbulent jet for a wide range of Strouhal numbers $\mathrm{St}_d = fd/u_0$. The initial boundary layer at the nozzle outlet was laminar (the form parameter of the boundary layer was $H \approx 2.6$). To turbulize it, the cylindrical exit section of the nozzle was increased successively, due to which the form parameter H was decreased to the value $H = 1.52$, typical of a turbulent boundary layer. The change in the mean velocity on the jet axis at a fixed point $x/d = 8$ as a function of St_d is presented in Fig. 2. It is essential to note here that for $\mathrm{St}_d \approx 2-5$ the velocity increases in both an initially laminar and initially turbulent boundary layer.

Figure 3 presents the relations $u/u_- = f(\mathrm{St}_d)$ at $x/d = 8$ for transverse acoustic irradiation of a jet at $L = 136$ dB and $u_0 = \mathrm{var}$, as well as at $u_0 = 20$ m/sec and $L = \mathrm{var}$. Experiments were carried out with an initially laminar

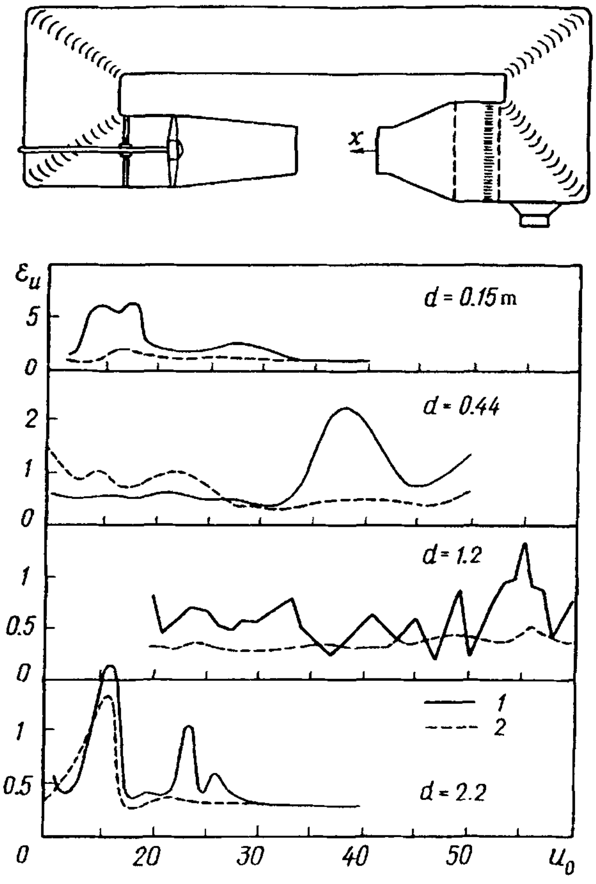

Fig. 4. Change in velocity fluctuations on the axis of the open working section of a wind tunnel at the point $x/d = 1$ in the absence (1) and presence (2) of acoustic excitation at $\mathrm{St}_d = 2$–5. u_0, m/sec.

boundary layer at the nozzle outlet. The experiments indicate a pronounced tendency toward enhancement of the effect of high-frequency acoustic excitation of the jet with increase in the sound pressure L or with decrease in the discharge velocity u_0. It is natural that the enhancement of the effect continues until the sound pressure attains a certain optimum level [1, 2]. In light of this, we may assume that in the experiments of [4] the absence of the turbulence attenuation effect upon high-frequency irradiation of a jet with an initially turbulent boundary layer can be due to an insufficiently high level of acoustic excitation.

As is known, in closed-type wind tunnels with an open working section, in a certain range of velocities self-oscillations appear that lead to a substantial increase in low-frequency longitudinal velocity fluctuations in the working section and in pressure fluctuations in the entire tunnel. The character of the self-oscillations in the tunnel is determined by two branches of acoustic feedback: through the reverse channel along the flow and through the working section opposite to the flow [1, 2]. The most common methods of damping this kind of fluctuations are reduced either to attenuation of regular formation of eddies in the mixing layer of the jet or to weakening of the influence of fluctuations in the free jet on fluctuations in the reverse channel. These self-oscillations can be suppressed by means of high-frequency acoustic irradiation of the mixing layer in the exit section of the nozzle [7], which leads to decay of coherent structures in the mixing layer, with the result that fluctuations of velocity and pressure in the working portion of the tunnel decrease. Flow in four wind tunnels with diameter of the nozzle $d = 0.15$, 0.44, 1.2, and 2.2 m was investigated; the mode of flow in the boundary layer at the nozzle outlet was controlled during the experiment. In the small tunnel ($d = 0.15$ m) there was an initially laminar boundary layer ($H = 2.5$–2.6); in the remaining tunnels there was a turbulent boundary layer with the typical values $H = 1.57$, 1.43, and 1.32. Figure 4 presents results of experiments that illustrate a decrease in velocity fluctuations in the working section of the tunnel on the axis at $x/d = 1$ upon exposure to high-frequency acoustic irradiation ($\mathrm{St}_d = 2$–5). In this case the sound emitter was located in the reverse channel of the wind tunnel (WT).

TABLE 1. Summary of Experimental Data on High-Frequency Acoustic Excitation of Turbulent Jets

Line No.	Type of flow, reference	Laminary boundary layer				Turbulent boundary layer				Notes
		St_d	St_θ	Re_θ	H	St_d	St_θ	Re_θ	H	
1	Jet [3]	1.5–6	0.006–0.024	500	2.59	1.5–6	0.025–0.1	835–2000	1.52	$x/d = 8$
2	The same [5]	1.5–3	0.005–0.01	942	2.1	1.5–3	0.01–0.02		1.6	$x/d = 9$
3	Mixing layer [6]		0.01–0.03	100–340	2.2–2.3		0.03–0.06	1565	1.49	$x/\theta_0 = 225$
4	Jet [8]	1.2–3.5	0.008–0.024	172–408	2.6					$x/d = 4$
5	The same [9]	7.74	0.01–0.02		2.6					$\varphi = 45–105^0$
6	The same [10]	3.77	0.0152	219	2.6					$\varphi = 31^0$
7	The same [4]	2.04–6.3	0.0065–0.02	220	2.6					$x/d = 2$
8	WT, $d = 0.15$ m [7]	1.3–3.1	0.002–0.0046	470	2.5					$x/d = 1$
9	The same $d = 0.44$ m					3.33	0.006–0.0075	2370	1.57	$x/d = 1$
10	The same $d = 1.2$ m					6.4–9.6	0.006–0.01	$(3-11)\times 10^3$	1.43	$x/d = 1$
11	The same $d = 2.2$ m					7.35	0.022	10^4	1.32	$x/d = 1$

Some results of experimental investigation of turbulent jets exposed to high-frequency acoustic irradiation for the cases of initially laminar or turbulent boundary layers (11 experiments) are listed in Table 1. It contains values of the Strouhal numbers St_d and St_θ, Reynolds number Re_θ, and form parameter H. The notes contain the sections (x/d or x/θ_0) for measuring velocities or velocity fluctuations and angles φ when the noise level is measured in the far field of the jet.

Data of experiments in which the turbulence attenuation effect was observed in both an initially laminar and initially turbulent boundary layer are given in lines 1-3; data of experiments in which the turbulence attenuation effect (or the decrease in pressure fluctuations in the far field of the jet) was investigated only for an initially laminar boundary layer are given in lines 4-6; data of an experiment in which, with transverse acoustic irradiation, the effect considered was obtained for an initially laminar boundary layer and was not discovered for an initially turbulent boundary layer are listed in line 7. Data of measurements carried out in wind tunnels with an open working section are given in lines 8-11 for an initially laminar boundary layer (line 8) and an initially turbulent boundary layer (lines 9-11).

We will mention one more example illustrating the realization of the effect of decrease in the noise of a propulsive jet in an NK-86 bypass engine [11], upon high-frequency acoustic irradiation of it. The Mach number at the nozzle outlet is $\mathrm{M}_0 \approx 1$, the gas temperature is $T = 870$ K, and the Reynolds number is $\mathrm{Re}_d = u_0 d/\nu = 5.8 \cdot 10^6$. The temperature in the boundary layer at the nozzle outlet was noticeably lower than in the flow core, since air arrived from the external loop of the TJE. With a high probability the initial boundary layer at the exit section of the nozzle can be assumed to be turbulent. A jet of diameter $d_1 = 0.95$ m was irradiated by 12 small peripheral jets that surrounded the central one and discharged from a common mixing chamber. The diameter of the small nozzles was $d_2 = 0.105$ m, and therefore the noise of the peripheral jets was high-frequency for the central jet. As is known, the maximum of the noise emitted by a turbulent jet corresponds to the Strouhal number range $\mathrm{St}_d = fd/u_0 = 0.2–0.5$. This equally refers to both the peripheral jets and the central jet. Since in both cases the discharge velocity was the same, then $f_1 d_1 = f_2 d_2$. Thus, the noise generated by the peripheral jets ($d_2 = 0.105$

m) is a source of high-frequency excitation for the central jet ($d_1 = 0.95$ m), i.e., $\mathrm{St}_d = f_2 d_1/u_0 = (f_2 d_2/u_0)(d_1/d_2) = (0.2-0.5)(d_1/d_2) = 1.81-4.53$. As a result, it turned out that this irradiation led to a decrease in the noise of the jet system by 2–3 dB in the far field and by up to 4 dB in the near field.

The above results show that the effect of turbulence attenuation in subsonic jets and, correspondingly, of a decrease in the noise generated by them on exposure to high-frequency acoustic irradiation is realized independently of the mode of flow in the boundary layer at the nozzle outlet. With increase in the initial turbulence of the flow, irrespective of the mode of the boundary-layer flow, the effect of attenuation of mixing upon high-frequency acoustic irradiation of the jet becomes less pronounced and is not realized already at $\varepsilon \approx 5\%$ [5].

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NOTATION

x, longitudinal coordinate; d, diameter of the exit cross section of the nozzle, m; θ_0, momentum thickness in the boundary layer of the nozzle, m; δ_0^*, displacement thickness, m; $H = \delta_0^*/\theta_0$, form parameter of the boundary layer; φ, angle between the jet axis and the direction from the center of the exit cross section of the nozzle to the point of measurement of pressure fluctuations, deg; u_0, discharge velocity, m/sec; u, mean velocity on the jet axis, m/sec; u_-, mean velocity on the jet axis in the absence of acoustic perturbations, m/sec; u', root-mean-square value of velocity fluctuations, m/sec; $\varepsilon_u = u'/u_0$, intensity of velocity fluctuations, %; f, frequency of acoustic perturbations, Hz; L, level of sound pressure, dB; $\mathrm{St}_d = fd/u_0$; $\mathrm{St}_\theta = f\theta_0/u_0$; $\mathrm{Re}_\theta = u_0\theta_0/\nu$; $\mathrm{Re}_d = u_0 d/\nu$; ν, kinematic coefficient of viscosity of the gas; T, temperature, K; M, Mach number.

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