TURBULENCE SUPPRESSION IN SUBSONIC JETS BY HIGH-FREQUENCY ACOUSTIC EXCITATION

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The influence of high-frequency acoustic excitation of a submerged round turbulent jet flowing out of a nozzle with both laminar and turbulent boundary layers at the nozzle outlet on the suppression of turbulent velocity fluctuations in the initial and transition regions of the jet is experimentally investigated. It is established that in the case of the turbulent boundary layer a higher excitation level is needed to realize the suppression effect than in the case of the laminar boundary layer.

1. Studies of the acoustic excitation of turbulent jets have shown that the jet characteristics can be affected in different ways depending on the excitation frequency. Thus, the mixing rate increases when the jet is exposed to low-frequency irradiation and decreases in the high-frequency case [1, 2]. Low-frequency excitation is more effective at the frequency f corresponding to the frequency of recurrence of the large-scale periodic structures at the end of the initial region of the non-irradiated jet. This frequency is on the Strouhal number range $St_d = fd/u_0 = 0.2$–0.5, where d is the nozzle outlet diameter and u_0 is the outflow velocity. The high-frequency excitation effect manifests itself at the frequency f characteristic of the small-scale periodic structures in the mixing layer near the nozzle outlet; in this case $St_d = 2$–5. Sometimes the Strouhal number is based on the momentum loss thickness θ_0 in the boundary layer at the outlet: $St_\theta = f\theta_0/u_0$.

The realization of both effects depends on the initial conditions of the flow, namely, the boundary layer flow regime and the turbulence level outside the boundary layer at the nozzle outlet. Unfortunately, in the first studies on the acoustic excitation of jets, the boundary layer flow regime was not monitored. Later, however, when this shortcoming was eliminated, the flow pattern turned out to be inconclusive.

Thus, it has been shown that in the case of the low-frequency acoustic excitation jet mixing is intensified irrespective of the boundary layer flow regime at the nozzle outlet and even at a rather high level of initial turbulence, $\varepsilon_0 = 5$ and 11% [1, 3]. In the case of high-frequency excitation, the results obtained for different states of the boundary layer are somewhat contradictory. Thus, in [4] the mixing attenuation effect was investigated only for laminar flow; in [5] it was possible to realize this effect for laminar flow but it did not take place in the presence of nozzle boundary layer turbulization; at the same time, in [3, 6] the effect was obtained for both laminar and turbulent flow regimes.

In this study, we will investigate the conditions of realization of the mixing attenuation effect (reduction of the velocity fluctuations on the jet axis within the initial region) for laminar and turbulent boundary layers at the nozzle outlet and various levels of the acoustic excitation.

2. The experimental setup consisted of a closed-circuit wind tunnel with an open test section; in order to obtain a sufficiently extended submerged jet ($x' = 6.5d$), the diffuser was removed and replaced by a collector (the x' coordinate is measured from the nozzle exit along the jet axis). The nozzle outlet diameter was $d = 0.15$ m and the outflow velocity was $u_0 = 18$ m/s. Static pressure measurements along the jet axis using a Pitot-Prandtl probe showed that the jet remained isobaric within the first six jet diameters. The Reynolds number was $Re = u_0 d/\nu = 1.9 \cdot 10^5$ and the turbulence level at the center of the nozzle exit section was $\varepsilon \approx 1\%$.

The velocity profiles in the nozzle outlet boundary layer (more exactly, at $x' = -2$ mm) were measured by a microhead consisting of a total-pressure tube with a flattened pressure orifice. The head was 0.36 mm high and 1.2 mm wide, while the dimensions of the pressure orifice were 0.2 and 1 mm, respectively. The tube was mounted in a remotely operated microminiature coordinate device with a displacement step of 0.02 mm. To turbulize the nozzle boundary layer, a turbulizer in the form of a wire ring 1 mm in diameter was attached to the inside surface of the nozzle at a distance $x' = -0.82$ mm from the nozzle edge. The measured data[1] are presented in Fig. 1. In Table 1 the values of the momentum loss thickness θ_0 and the boundary layer form parameter $H = \delta^*/\theta_0$ calculated from these profiles are given;

[1]The experiments on the determination of the velocity profiles in laminar and turbulent boundary layers were performed by A. V. Zosimov and A. G. Prozorov, respectively.

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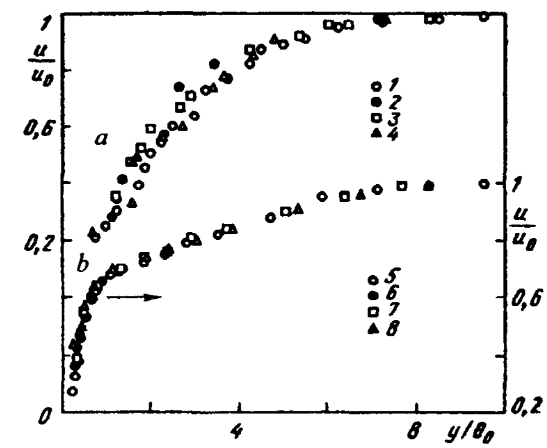

Fig. 1. Mean velocity profiles at the nozzle exit in the laminar (*a*) and turbulent (*b*) boundary layers (notations for the points explained in Table 1).

the data are presented for laminar (columns 1 to 4) and turbulent (columns 5 to 8) boundary layers. From these data, the values of the same parameters at $u_0=18$ m/s were determined by interpolation and turned out to be $\theta_0=0.22$ mm and $H=2.44$ for the laminar boundary layer and $\theta_0=0.76$ mm and $H=1.54$ for the turbulent boundary layer.

A G3-33 pure-tone generator was used as a sound source. The transverse acoustic excitation of the jet was achieved by means of an electrodynamic sound radiator with a rectangular, 400 by 200 mm, diffuser. Using this radiator, it was possible to obtain a sound pressure level, L, at the nozzle outlet ranging from 95 to 130 dB; along the nozzle edge the level varied only slightly ($\Delta L \sim \pm 1$ dB). The value of L was measured with a B & K electroacoustic system.

To measure the mean longitudinal velocity in the jet, u, and the rms value of the longitudinal velocity fluctuations, u', we used a DISA 55M01 hot-wire anemometer supplied with 55D31 and 55D35 voltmeters. The hot-wire anemometer signal was recorded on magnetic tape with further spectral analysis in narrow ($\Delta f=7$ Hz) or one-third-octave frequency bands.

In measuring the flow parameters along the jet axis and in jet cross-sections, the anemometer probe with a single 5 μm diameter wire was secured in the coordinate device, which ensured probe displacement in both the longitudinal, x, and transverse, y, directions ($y=0$ on the jet axis).

The effect of the acoustic excitation of a jet at a fixed outflow velocity is most easily judged from the law of variation of the jet's mean velocity $u(x)$ and the longitudinal velocity fluctuations $u'(x)$ along the jet axis ($x=x'/d$) with and without excitation. As an example, in Fig. 2 we present the plots $u/u_0=\varphi_1(x)$ and $\varepsilon(x)=u'(x)/u_0=\varphi_2(x)$ for an unexcited jet (*1*) and for the same jet in the presence of high-frequency longitudinal excitation with $St_d=2.75$ and $\varepsilon_{ac}=u'_{ac}/u_0=0.07\%$, where u'_{ac} is the fluctuation velocity in the acoustic wave ($u_0=20$ m/s, $\varepsilon_0=0.5\%$, $d=10$ mm, $Re_d=1.4\cdot10^4$, and $L=110$ dB); the plots are taken from [2]. The initial boundary layer in that work was apparently turbulent, since there was an annular groove in the inside surface of the nozzle which operated as a kind of a turbulizer. It is remarkable that at different x the acoustic effect manifests itself in different ways. If the ratios u/u_* and u'/u_*' for different x are taken as a measure of the manifestation of the effect, then from Fig. 2 we obtain the values given in Table 2.

Here, the flow parameters in the absence of acoustic disturbances are marked by an asterisk. Naturally, under other experimental conditions (initial conditions of jet outflow, longitudinal or transverse excitation) the ratios u/u_* and u'/u_*' will change; however, the general trend remains the same: the effect becomes more pronounced as x' increases on the range from 0 to 9.

3. The experiments were carried out for two jet cross-sections: (*a*) $x=2$ and (*b*) $x=6$, with laminar (*1*) and turbulent (*2*) initial boundary layers. The dependence of u/u_* and u'/u_*' on the sound pressure level L is plotted in Fig. 3. It can be seen that for the laminar initial boundary layer, acoustic irradiation at $u_0=18$ m/s, $f=500$ Hz, $St_d=4.17$, and $L > 115$ dB leads to a noticeable (15–18%) reduction in the rms velocity fluctuations on the jet axis in both cross-sections; for the turbulent initial flow regime, a similar reduction is achieved only at $L=120$–130 dB. At $L=130$ dB the effect is nearly the same for both flow regimes in the initial boundary layer ($u'/u_*'=0.82$–0.83).

The effect of high-frequency irradiation on the variation of the mean velocity along the jet axis is somewhat similar. At $x=2$ the effect is only slight; however, at $x=6$ a noticeable increase in the mean velocity was recorded. This increase is greater for a laminar initial boundary layer; however, when the sound pressure level $L=130$ dB is reached, the same

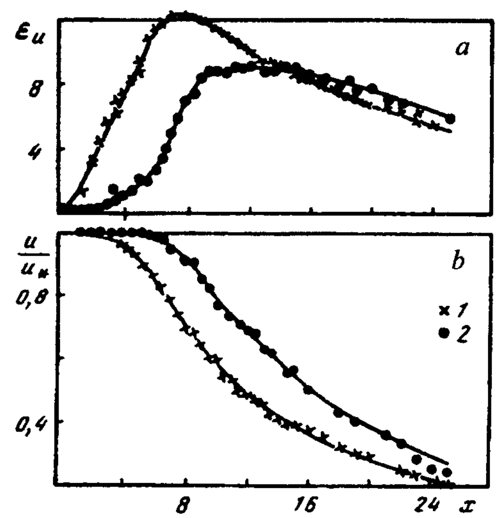

Fig. 2. Distributions of the longitudinal velocity fluctuations (*a*) and the mean velocity (*b*) along the jet axis; *1*, unexcited jet and *2*, excited jet at $St_d = 2.75$.

TABLE 1

N	1	2	3	4	5	6	7	8
u_0,m/s	16.4	22	30	40	10.5	15.2	20.8	24.2
θ_0, mm	0.22	0.20	0.17	0.14	0.83	0.77	0.75	0.70
H	2.5	2.34	2.21	2.31	1.57	1.56	1.52	1.51

TABLE 2

x	1	2	3	4	5
u/u_*	1.02	1.04	1.16	1.37	1.43
u'/u_*'	0.14	0.18	0.23	0.56	0.68

value $u/u_* = 1.06$ is attained irrespective of the boundary layer flow regime. The variation of the mean velocity u/u_0 and the intensity of the longitudinal velocity fluctuations $\varepsilon_u = u'/u_0$ along the jet axis is plotted in Fig. 4 for laminar (*1*) and turbulent (*2*) initial boundary layers in the presence of acoustic excitation ($u_0 = 18$ m/s, $f = 500$ Hz, $L = 130$ dB) and in its absence (*3*). In the latter case, the flow regime in the initial boundary layer has practically no influence on the variation of u/u_* and ε_u along the jet axis (x). In conclusion, we present the one-third-octave spectra of the longitudinal velocity fluctuations on the jet axis in the section $x = 5$ (Fig. 5). Here, the ordinate is $\Delta L = L^u - L_*^u$, where L^u is the velocity fluctuation level at the frequency f, while L_*^u corresponds to the total level of the velocity fluctuations in the absence of acoustic excitation; L is measured in dB and f in Hz.

It is worth checking whether and to what extent the results obtained agree with those of earlier experiments [6] and [3–5], in which the turbulence suppression effect was investigated under controlled initial conditions with both laminar and turbulent boundary layers. The data of the four experimental studies are given in Table 3 for laminar and turbulent flow regimes in the nozzle outlet boundary layer (superscripts l and t, respectively). The first two studies (rows 1 and 2) were made for longitudinal acoustic excitation, while the second two (rows 3*a*, 3*b* and 4*a*, 4*b*) for transverse excitation. Rows 1 to 4 correspond to the data of [6], [3], [5], and the present study.

The studies performed also showed that in the case of low-frequency excitation the introduction of disturbances into the nozzle boundary layer (by means of a transverse groove on the inside surface of the nozzle or a low barrier or a wire screen installed in the region of the nozzle surface through which acoustic disturbances are introduced along a waveguide [7]) has only a slight effect. At the same time, in the case of high-frequency excitation the introduction of disturbances considerably attenuates and may even suppress the mixing slowdown effect. This effect is also attenuated by an increase in the initial turbulence level, almost dying out at $\varepsilon = 5\%$.

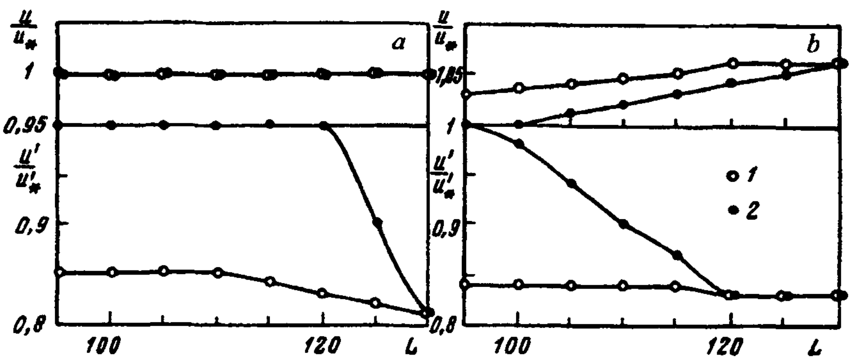

Fig. 3. Influence of the excitation level on the mean and fluctuation velocities on the jet axis for laminar (*1*) and turbulent (*2*) boundary layers: *a*, $x=2$ and *b*, $x=6$.

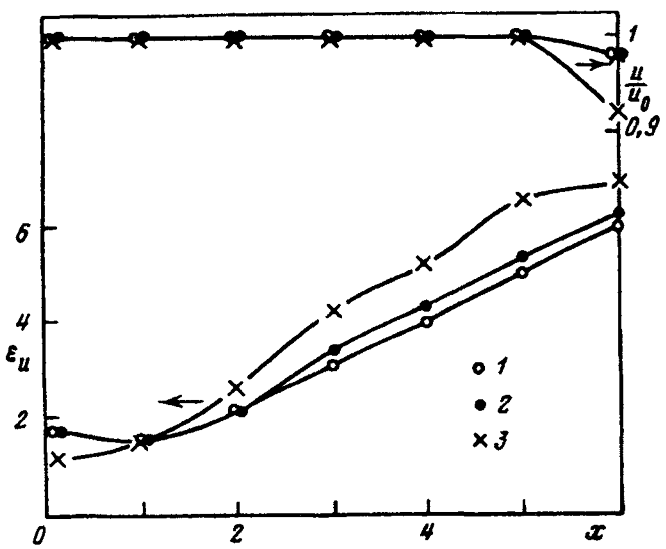

Fig. 4. Variation of the mean velocity and the longitudinal velocity fluctuations along the jet axis: *1* and *2*, laminar and turbulent boundary layer flow regimes with acoustic excitation, *3*, without excitation.

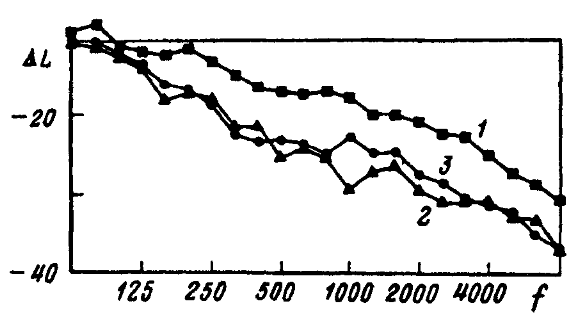

Fig. 5. Spectra of the longitudinal velocity fluctuations on the jet axis in the $x=5$ cross-section: *1*, without excitation, *2* and *3*, laminar and turbulent boundary layer flow regimes with acoustic excitation.

TABLE 3

No.	d, mm	u_0, m/s	ε_0, %	$Re_d \cdot 10^{-5}$	St_d	L, dB	ε_{ac}, %	x	H'
1	25	30	–	0.52	5	120	0.16	8	2.59
2	88	51	0.15	3.14	2.8	130	0.29	9	2.1
3*a*	120	8	0.8	0.67	6	115	0.33	2	2.6
3*b*	120	8	0.8	0.67	6	115	0.33	4	2.6
3*c*	120	8	0.8	0.67	6	115	0.33	8	2.6
4*a*	150	18	1	1.89	4.17	130	0.83	2	2.44
4*b*	150	18	1	1.89	4.17	130	0.83	4	2.44
4*c*	150	18	1	1.89	4.17	130	0.83	6	2.44

TABLE 4

$St_\theta^l \cdot 10^{-3}$	Re_θ^l	u^l/u_*	u'^l/u_*'	H'	$St_\theta^t \cdot 10^{-3}$	Re_θ^t	u^t/u_*	u'^t/u_*'
10	218	1.13	–	1.52	83	877	1.20	–
7	942	1.12	–	1.6	16	2060	1.12	–
15	220	–	0.72	1.65	36	401	–	1
15	220	–	0.80	1.65	36	401	–	1
15	220	–	1.0	1.65	36	401	–	1
6	271	1	0.82	1.54	21	958	1	0.82
6	271	1	0.76	1.54	21	958	1	0.82
6	271	1.06	0.83	1.54	21	958	1.06	0.83

4. Apparently, there is no conclusive view with regard to the mechanism of this effect. It is well known that for a laminar initial boundary layer, the effect of periodic disturbances on the unstable mixing layer is greatest on the frequency range corresponding to maximum growth rates of the disturbances near the nozzle edge [4]. According to linear stability theory [8], the maximum growth rate is attained at $St_\theta = 0.017$. The mechanism of suppression of fluctuations on the jet axis by high-frequency disturbances is determined by the accelerated transition to turbulence in the shear layer which retards the formation of large-scale vortices. This was questioned in [5] on the grounds that the fluctuation levels on the axis of an acoustically excited jet should then take a certain intermediate value between the limiting values corresponding to the laminar and turbulent initial boundary layers without excitation. However, this is not the case, as confirmed by the present results (cf. Fig. 4).

A somewhat different explanation for the effect under consideration, which is valid for both laminar and turbulent initial boundary layers, was given in [5, 9]. Essentially, under high-frequency excitation tandem ring vortices are generated in the mixing layer near the nozzle ($x < 1.5$), the distance between the vortices being determined by the excitation frequency and the outflow velocity. This leads to a situation in which in the above-mentioned zone of the mixing layer the low-frequency disturbances, which make the main contribution to the turbulence energy, are suppressed under the action of the high-frequency sound. This is confirmed by experiments made at a low initial turbulence level: the growth rates of low-frequency disturbances corresponding to the Strouhal numbers $St_d = 1.3–2.5$ decrease at $x < 1$. Therefore, the sound-generated small-scale vorticity modulation along the shear layer results in the suppression of low-frequency disturbance growth and stabilization of the shear flow.

The specially-designed experiments described in [10] showed that the mechanism of turbulence suppression in a shear flow by high-frequency excitation can be explained neither by interaction between Tollmien-Schlichting waves in the nozzle boundary layer and Kelvin-Helmholtz waves in the shear layer nor by the turbulization of the initial boundary layer by acoustic excitation.

Summary. The attenuation of mixing in a jet subjected to high-frequency acoustic excitation, that is the partial suppression of turbulence, is realized independently of the boundary layer flow regime at the nozzle outlet. However, for a turbulized initial boundary layer, a higher level of acoustic excitation is needed.

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