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INFLUENCE OF NOZZLE VIBRATIONS ON THE AERODYNAMIC CHARACTERISTICS OF A JET

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The results of investigations of the aerodynamic characteristics of turbulent jets issuing from nozzles and subjected to the action of various kinds of low-frequency vibrations — transverse, longitudinal, and torsional (during axisymmetric vibrations of the nozzle around the longitudinal axis) — are presented. Data on the laws governing changes in the average and pulsation velocities along the jet axis, as well as on the spectra of velocity pulsations in the zone of jet mixing, have been obtained. It has been established that at low-frequency vibrations of the nozzle a noticeable intensification of jet mixing is attained. The same effects as on acoustic excitation of a jet are observed. The experiments were carried out at Reynolds numbers $Re = 2{\cdot}10^4$–$8{\cdot}10^4$.

Keywords: *aerodynamic characteristics, turbulent jets, low-frequency vibrations of a nozzle, mixing intensification, spectrum of velocity pulsations.*

Introduction. It is known [1, 2] that the aerodynamic characteristics of a turbulent jet can be altered either by acoustic irradiation or by periodic influence on the jet flow in its initial section. Such an influence can be implemented by creating a periodic change in the rate of gas flow through a nozzle, by nozzle vibrations, or by exciting the mixing layer at the nozzle edge with the aid of a vibrating tape. The above-enumerated means of a possible change in the turbulent jet characteristics are based on the fact that in the nozzle exit section periodic circular vortices are generated, the presence of which, as well as their interaction with one another, substantially change the flow in the mixing layer of the initial section of the jet. These means can be used for altering the aerodynamic characteristics of a turbulent jet, as well as of the acoustic ones directly related to the former. At the same time, the change of the aerodynamic and acoustic characteristics of a turbulent jet exposed to acoustic periodic irradiation may also have undesirable consequences. In particular, this relates to the noise generated by an exhaust jet of jet engines — the so-called problem of excess noise of a turbulent jet.

In [2], it is noted that the noise of the jet streams of aircraft engines exceeds the predicted values. One of the possible reasons for this is the presence of internal sources of noise (compressor, combustion chamber, turbine) that excite a jet and increase its broadband noise. But there may exist another interpretation of this phenomenon. Since the elements of the construction of an aircraft engine are exposed to the effect of various kinds of vibrations, precisely the vibrations of a nozzle may lead to a change in the acoustic characteristics of a jet, i.e., intensification of its mixing and an undesirable increase in the noise radiated by a jet.

Statement of the Problem and Measurement Technique. The principal purpose of the present work is to clarify the possibility of intensifying the mixing of the jet that issues from a nozzle and that is subjected to the effect of different kinds of vibrations: transverse, longitudinal, and torsional (axisymmetric vibrations of a nozzle around its longitudinal axis).

In earlier investigations [2–4], it has been established that transverse vibrations of a nozzle exert a qualitative influence on the averaged and pulsation characteristics of a flow in the zone of mixing of a turbulent jet, just as the acoustic irradiation of it. Two effects are being realized: intensification of mixing in the case of low-frequency vibrations and attenuation of mixing during high-frequency vibrations of a nozzle. In the latter case, acoustic irradiation is more efficient. Since in the present work the task to elucidate the possibility of intensification of turbulent mixing of

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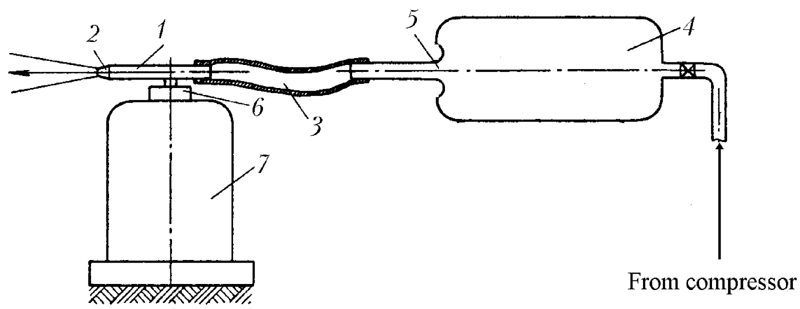

Fig. 1. Schematic diagram of the setup for transverse vibrations: 1, pipeline; 2, nozzle; 3, flexible hoze; 4, damping chamber; 5, metering nozzle; 6, rest; 7, vibrator.

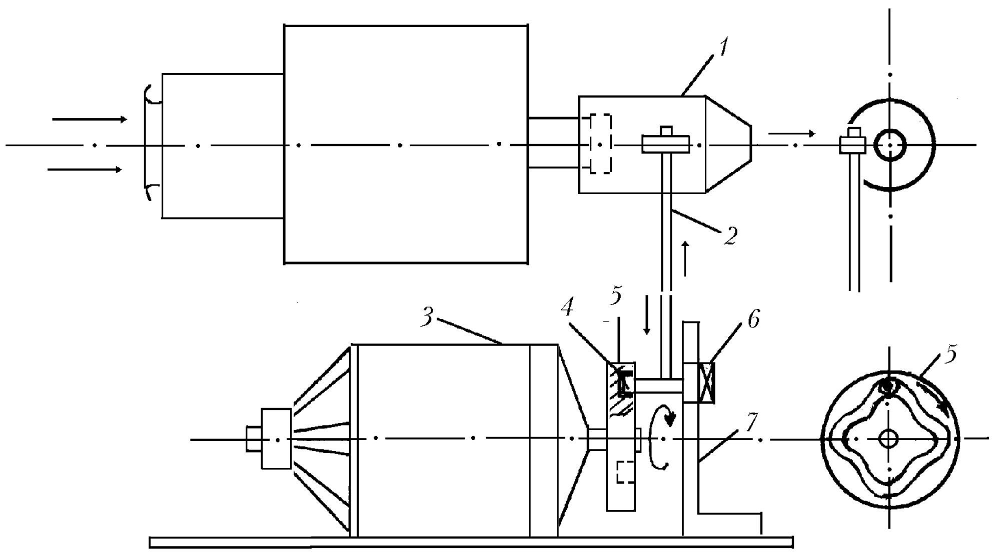

Fig. 2. Schematic diagram of the setup for rotational vibrations of the nozzle: 1, nozzle; 2, rod; 3, electric motor; 4, faceplate; 5, bearing; 6, plate; 7, angular support.

a jet was posed, the experiments described below were carried out for low-frequency vibrations of a nozzle, i.e., at f = 20–40 Hz. Measurements were made on setups with the diameters of exit sections of nozzles d = 0.01–0.03 m. The velocity of jet escape at the nozzle cut changed within the range u_0 = 10–75 m/sec, which corresponds to the range of Reynolds numbers $\mathrm{Re} = u_0 d/\nu = 2{\cdot}10^4$–$8{\cdot}10^4$. Turbulence at the nozzle cut on the nozzle axis was ε_0 = 1%. The amplitude of transverse and longitudinal vibrations of the nozzle u was equal to 0.0125 m and 0.005 m, respectively, and the maximum angle of its torsional vibrations was $\alpha = 8^{\mathrm{o}}$.

To measure average and pulsation velocities, a set of the 55M Disa thermoanemometric equipment was used.

In experiments with a jet issuing from a transversely vibrating nozzle, a device described in detail in [3] was used (Fig. 1). The jet studied issued from a pipeline 1 ending in a nozzle 2 of diameter d. The pipeline was connected by a flexible hose 3 with a damping chamber 4 of an air-blowing setup with a metering nozzle 5. The rest 6 onto which the pipeline was installed had been fastened to the vibrator platform 7. The vibrator platform performed translational harmonic vibrations in the vertical plane. The frequency of the platform vibrations was assigned with the aid of a pure tone generator. On the vibrator platform and on the nozzle (near its exit section) vibro-pickups were installed; their signals were fed to a spectrometer. The frequency of vibrations f and their amplitude a were measured.

To carry out torsional vibrations of the nozzle, a device has been developed the basic diagram of which is presented in Fig. 2. The nozzle 1 can rotate around its own axis. A rod 2, which performs a reciprocate motion, is connected through a ball bearing to a special unit on the nozzle body. To ensure such a motion on the axis of an

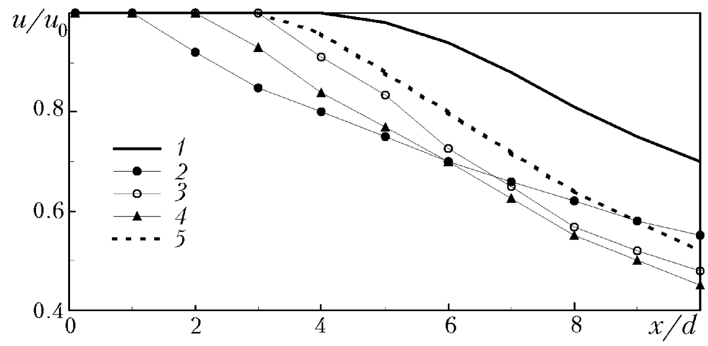

Fig. 3. Comparison of the change in the average velocity along the jet axis in the case of various means of vibrational effect: 1, jet with no effect; 2, transverse vibrational excitation; 3, longitudinal vibrational excitation; 4, torsional vibrational excitation; 5, low-frequency acoustic excitation at $\mathrm{St_s}$ = 0.389, u_0 = 20 m/sec, L = 120 dB.

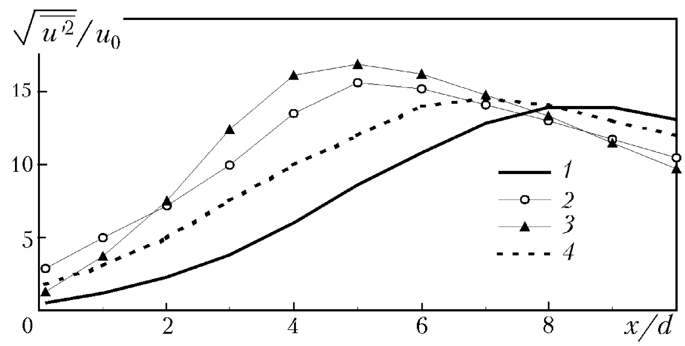

Fig. 4. Comparison of the change in the pulsational velocity along the jet axis in the case of different means of vibrational effect: 1, jet with no effect; 2, longitudinal vibrational effect; 3, torsional vibrational effect; 4, low-frequency acoustic excitation at $\mathrm{St_s}$ = 0.389, u_0 = 20 m/sec, L = 120 dB.

electric motor 3, a faceplate 4 was fixed in which a shaped groove had been made. The bearing 5 moves along this groove; the axis of the bearing is connected with the rod and a plate 6 that is located in the vertical cut of an angular support 7. During the rotation of the electric motor with the faceplate the bearing moves in the shaped groove and causes the rod to perform a reciprocate motion. Four vibrations occur during one revolution of the faceplate. The amplitude of the rod motion corresponds to the rotation of the nozzle by 8°. The frequency of vibrations depends on the number of motor revolutions that can be regulated by the voltage supplied to the motor.

In experiments with a jet issuing from the nozzle vibrating in the longitudinal direction, a similar device was used, except that the rod was not connected to the unit on the nozzle body but transmitted vibrations to a "bell-crank" by means of a ball joint fixed on the rod. In turn, by means of the ball joint, the bell-crank transformed vertical vibrations of the rod into the longitudinal vibrations of the nozzle; the latter could move, vibrating with the amplitude a = 5 mm.

The noise levels generated during operation of all the three devices described above were relatively small and could not exert an effect on the aerodynamic characteristics of the jet. This is proved by the results of measurements presented in [2], where an analysis of the dependence of the aerodynamic characteristics of a jet on the level of acoustic effect was carried out.

Experimental Results and Their Analysis. Figure 3 demonstrates the change in the average velocity along the jet axis over the first dozen calibers for three type of vibrational effect on the nozzle (transverse, longitudinal, and torsional vibrations). Shown there is also the change in the velocity along the jet axis in the absence of vibrations and during low-frequency acoustic irradiation of the jet. A clearly seen tendency is to be noted: in the jet issuing from the nozzle that is subjected to any of the indicated types of low-frequency vibrations, the average velocity along the jet

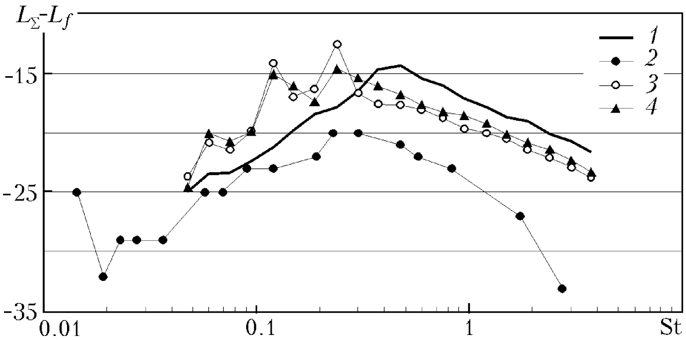

Fig. 5. Influence of vibrational effect on the spectral characteristics of jet velocity pulsations: 1, jet with no effect; 2, transverse vibrational excitation; 3, longitudinal vibrational excitation; 4, torsional vibrational excitation.

axis falls much more rapidly than for the jet issuing from a nonvibrating nozzle, and the length of the initial section of the jet decreases noticeably. In this case, the low-frequency vibrations of the nozzle exert the same effect on the jet as the low-frequency acoustic irradiation of it. The quantitative difference in the obtained data for different types of nozzle vibrations is quite explanable. This is due to the fact that the efficiency of the action of nozzle vibrations on the intensification of jet mixing depends on the amplitude of vibrations, just as the efficiency of the action of acoustic irradiation depends on the intensity of sound [2, 4].

The change in the pulsation velocity along the axis of the jet issuing from a vibrating nozzle (longitudinal and torsional vibrations) in the absence of vibration and in the course of low-frequency acoustic irradiation of the jet is shown in Fig. 4.

From the graphs presented, it follows that the low-frequency vibrations of the nozzle, as well as the low-frequency acoustic effect, intensify the process of jet mixing. This leads to an increase in the intensity of velocity pulsations in the initial and transient sections of the jet, to thickening of the mixing layer, enhancement of the ejecting ability of the jet, and to the shortening of the initial section length. It should be noted that an increase in the velocity pulsations on the jet axis is observed only at a distance of no more than eight calibers from the nozzle cut. Further downstream the pulsational characteristics of the jet practically do not differ from the corresponding characteristics of the initial jet. Earlier the same results were obtained for a jet issuing from a nozzle vibrating transversely [3].

Figure 5 presents 1/3-octave spectra of the longitudinal components of the jet velocity pulsations measured on its axis at $x/d = 5$. From this, in particular, it follows that low-frequency vibrations of a nozzle, just as low-frequency acoustic irradiation of a jet, leads to a noticeable redistribution of the energy of its pulsational motion to the side of low frequencies. Further downstream this effect becomes less and less evident, and over the main section the spectra of velocity pulsations of an excited and unexcited jet differ little. A similar phenomenon is observed in the case of different forms of action on the jet [1–6].

Conclusions. The results obtained point to a sufficient efficiency of the effect of low-frequency vibrations of a nozzle (longitudinal, transverse, and torsional) on the aerodynamic characteristics of a jet.

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NOTATION

a, amplitude of vibrations, m; d, outlet diameter of a nozzle, m; f, frequency, Hz; L, level of sonic pressure, dB; Re, Reynolds number; St = fd/u_0, Strouhal number; u_0, jet efflux velocity, m/sec; u, average velocity on the jet axis, m/sec; u', longitudinal velocity pulsations, m/sec; x, longitudinal coordinate, m; α, angle of torsional vibrations, deg; ε, turbulence degree, %; ν, kinetic coefficient of viscosity, m^2/sec. Subscripts: 0, initial value; f, value in the 1/3-octave band at frequency f; s, sonic effect; Σ, total value.

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