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CERTAIN FEATURES OF COHERENT FLOW STRUCTURE DEVELOPMENT IN THE INITIAL SECTION OF THREE-DIMENSIONAL TURBULENT JETS

L. N. Ukhanova and L. N. Voitovich

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Results of an experimental investigation of regular, large-scale, vortex structures in three-dimensional submerged jets are elucidated.

Regularities in the propagation of three-dimensional turbulent submerged jets issuing from nozzles with rectangular output section have attracted the attention of many researchers in recent years. A number of distinctive features inherent to flows of this kind have been revealed as a result of detailed experiments they performed [1-4].

Firstly, it has been shown that three characteristic axial velocity attentuation domains are clearly traced in such jets: an initial section, or a domain of constant axial velocity ($u_c \sim$ const), a transition section where the attenuation law for the axial velocity of plane jets ($u_c^2 \sim x^{-1}$) is valid for sufficiently large aspect ratios of the nozzle output section, and an axisymmetric flow section ($u_c^2 \sim x^{-2}$) far from the nozzle.

Moreover, it has been detected that propagation of a three-dimensional submerged jet is accompanied by unique deformations of its cross section, similar to that also inherent to three-dimensional wakes [5]. A result of this deformation is the "inversion" of the major and minor transverse axes of the jet.

This feature of three-dimensional jet development is associated with the nonuniformity of its expansion in two mutually perpendicular planes of symmetry, which is especially noticeable in the initial and transition flow sections. For larger aspect ratios of the nozzle output section, as well as for jet escape from a slot with sharp edges, even jet contraction in the direction of the major transverse flow axis (along the span of the orifice) is observed in these flow domains. Upon radical contraction of the jet along the major transverse axis, the corresponding mean velocity profiles take on a "saddle" shape.

These features of three-dimensional turbulent jet development are visibly due to large-scale periodic structures that are formed in mixing layers near the nozzle. The transverse flows induced by this ordered system of closed vortex formations are indeed the reason for the observed three-dimensional jet deformations [1, 6, 7].

The large-scale ordered vortex formations inherent to turbulent shear flows are investigated in detail in plane and axisymmetric jets [8], which are substantially the limit cases for a three-dimensional jet. However, the coherent structure of three-dimensional jets when the regularities of their development are determined by spatial effects to a significant extent has not been investigated in practice.

The fundamental parameters of a coherent structure in the initial section of three-dimensional turbulent jets formed under different initial escape conditions are experimentally

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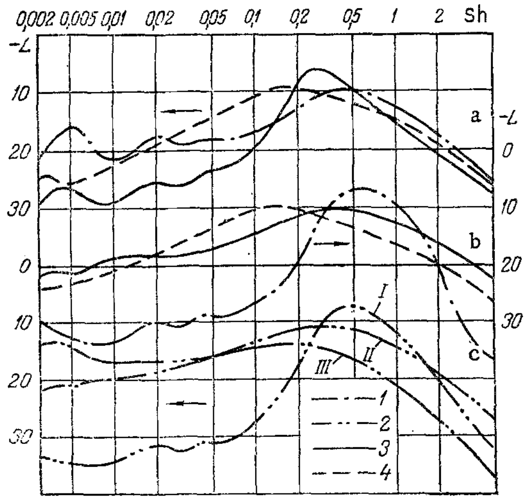

Fig. 1. Longitudinal velocity fluctuation spectra on the axis of three-dimensional jets issuing from a nozzle λ = 9.85 (a) and a slot λ = 9.77 (b and c, curve I): 1) $\bar{x}$ = 1; 2) 1.5; 3) 3; 4) 7, and in mixing layers of a jet from the slot λ = 9.77 (c): II) mixing layer evolved from the larger edges of the slot; III) from the smaller edges. L, dB.

investigated in this paper. Certain results of the first stage of these investigations have been presented in [9].

Submerged air jets issuing at a low subsonic speed from nozzles with rectangular output section were studied. The experimental apparatus was an underwater channel of 60 × 120 mm rectangular section and 1130-mm length, to which nozzles profiled in a Vitoshinskii curve were attached. The nozzles were identical in length (100 mm) and of approximately tenfold waisting. The aspect ratios of the rectangular output holes were λ = 2.04, 4.77 and 9.85. Moreover, a jet issuing from a rectangular slot with sharp edges cut in a thin flat plate whose aspect ratio was λ = 9.77 was examined.

An identical air mass flow rate was assured in all the flow variants studied. Since the areas of the output sections of the nozzles used were somewhat distinctive, the escape velocity varied between 69 and 72 m/sec. The Reynolds number computed with respect to the nozzle width and the escape velocity hence varied in the area of $(4\text{-}9)\cdot 10^4$.

The mean velocity distribution in the nozzle output section was practically uniform over both transverse axes. The intensity of the turbulence estimated by means of the magnitude of the longitudinal velocity fluctuations was 0.4-0.5% at the center of the nozzle output sections.

The fundamental laws of longitudinal mean and fluctuating velocities were studied by using a constant-resistance thermoanemometer and unifilar thermal caps [9]. The notable influence of the initial escape conditions, determined by the magnitude of λ and the profiling of the nozzle apparatus, on the three-dimensional jet formation and development was noted. All the above-mentioned features of three-dimensional jet propagation were observed.

Since the regularities obtained for the change in the fundamental parameters of the three-dimensional jets under consideration in the first stage of the investigations and represented in [9] are in good agreement with known analogous data of other authors, obtained under similar conditions of jet flow formation, there is no need to examine them in detail in this paper. It should just be noted that the nature of the turbulence intensity distribution along the flow axis (see [9]) indicates laminar boundary-layer states in the output sections of the profiled nozzles being utilized [10]. The longitudinal fluctuation velocity intensity in the jet issuing from the rectangular slot in the thin plate exceeds somewhat the corresponding intensity in the jet issuing from the nozzle.

The coherent structure parameters in the three-dimensional jets being studied were estimated from the results of a spectral and correlation analysis of the longitudinal velocity fluctuations.

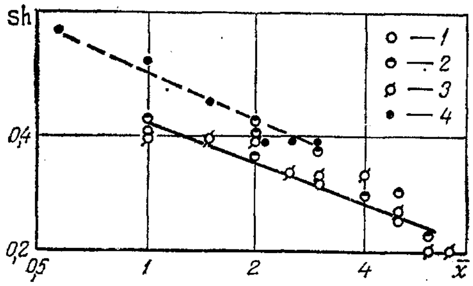

Fig. 2. Change in the Strouhal number corresponding to coherent structures along the initial section axis of three-dimensional jets issuing from rectangular nozzles of different aspect ratio: 1) $\lambda = 2.04$; 2) 4.77; 3) 9.85 (solid line) and from a slot with sharp edges: 4) $\lambda = 9.77$ (dashed).

Since the velocity fluctuations in the potential core domain are caused principally by the large-scale coherent flow structure, certain features of the development of this latter can be observed by the change in the velocity fluctuation spectrum nature at different points along the axis of the initial section. The characteristic frequency distributions of the velocity fluctuations in a number of points on the axis of the initial section and in the mixing layers being evolved from the nozzle larger and smaller edges obtained by using a one-third octave analyzer are represented in Fig. 1 for two nozzles.

The appearance of an evident peak in the velocity fluctuation spectra on the three-dimensional jet axis, which indicates the origination of an ordered vortex structure in the mixing layers, was observed at distances on the order of $\bar{x} \geqslant 2$ from the profiled nozzles and was tracked to $\bar{x} = 5$-6. No dependence on the aspect ratio was detected within the range of λ variation between 2 and 10.

In the jet issuing from the slot such a peak appeared in the frequency spectra considerably closer to the output orifice (for $\bar{x} = 0.6$), and vanished at distances $\bar{x} \geqslant 3$ (see Fig. 1).

In the mixing layers where the contribution of disordered velocity fluctuations to the turbulence energy is high in a broad frequency band, no clear peaks were detected at the characteristic frequencies. In the mixing layer evolving from the larger nozzle edge, the fluctuation spectrum is shifted somewhat to the high frequency domain as compared with the analogous spectrum in the layer from the shorter edges.

Exactly as in plane and axisymmetric jets, the characteristic frequency for an ordered structure is diminished along the initial section of three-dimensional jets, which is visibly a result of mutual interaction of the large-scale formations, their pairwise merging, and the change in their size. The dependence of the Strouhal number of the longitudinal coordinate obtained from the results of measuring the characteristic frequencies in all the jet flows under consideration is presented in Fig. 2. An analogous change in the characteristic value of the Strouhal number along the initial section of a submerged circular jet was obtained in [11] in investigations of pressure fluctuation spectra.

The longitudinal and transverse scales of regular vortex structures in the initial section of three-dimensional jets were determined by means of two-point spatial and space-time correlations of the longitudinal velocity fluctuations. Both points on the jet axis and points in the mixing layers on the lines of the nozzle edges in both planes of symmetry were selected here as the reference points at which the fixed thermal caps were rigidly fastened.

Distributions of the spatial correlation coefficients were obtained from the selected reference points along the three coordinates axes. The moving cap was displaced from the reference point in only the stream direction in the measurements of the space-time correlation coefficients. The correlation coefficients were estimated both by means of the total signals from the thermal caps and in the three-octave frequency bands corresponding to the frequency of the coherent structure.

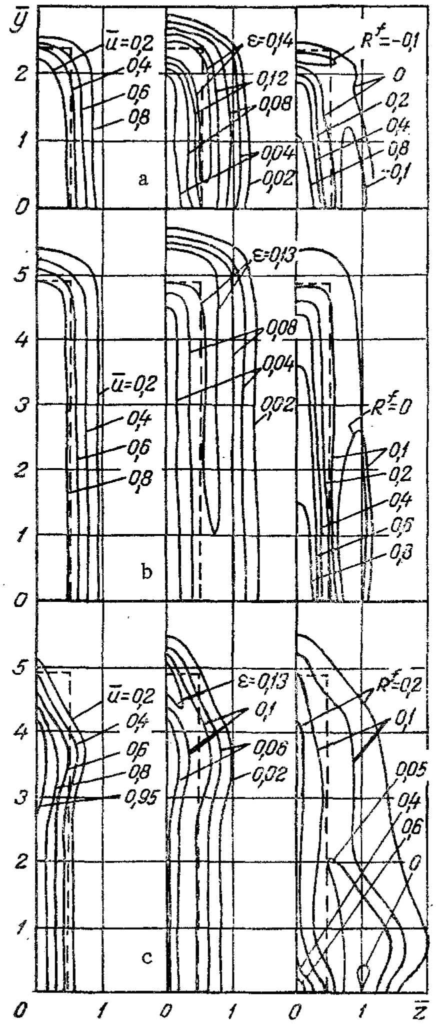

Fig. 3. Distribution of equal-velocity, equal-correlation and equivalent intensity lines of the turbulence in the transverse section $\bar{x}$ = 3 of three-dimensional jets issuing from the profiled nozzles λ = 4.77 (a) and 9.85 (b) and from the slot in a plane diaphragm λ = 9.77 (c); dashed lines are output section outline.

As has already been noted in [9], the distributions of the spatial correlation coefficients along the axis of the initial flow section are quasiperiodic in nature, even in the comparison of the total signals, which is still another direct confirmation of the existence of a coherent structure in this domain. In order to extract the regular vortex structures in the mixing layers, it would be necessary to perform measurements in the appropriate frequency bands.

The longitudinal and transverse vortex structure scales were determined by means of the coordinate of the first zero value of the correlation coefficient in the appropriate distributions. Tendencies to enlarge both the longitudinal scale of these vortices and the distance separating them along the flow were observed. The longitudinal scale varied approximately from 0.3h to h along the initial section of three-dimensional jets, while the distance between the vortices grew from 2h to 3h. The transverse dimension of the characteristic vortices in the plane of symmetry parallel to the smaller sides of the nozzle output section was of approximately the same magnitude as the longitudinal value.

The intensity of coherent structure degeneration and their convective velocity were determined from the results of measuring the space—time correlation. It turns out that coherent structure degeneration occurs with different intensity in the initial section of three-dimensional jets along mixing layers evolving from the larger and smaller edges of the nozzle. The coherent structure degenerated considerably more rapidly in the jet issuing from

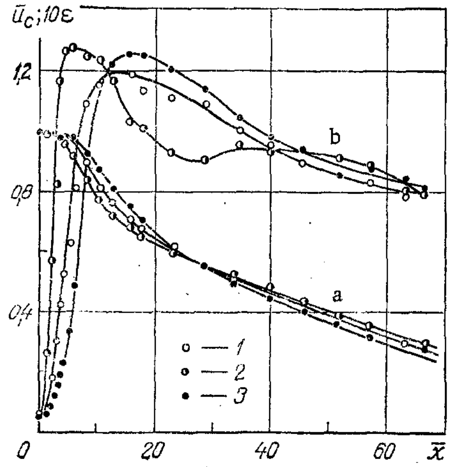

Fig. 4. Change in the mean velocity (a) and longitudinal velocity fluctuation (b) along a three-dimensional jet axis in the absence of a sound field, for low- and high-frequency sound irradiation: λ = 9.85; 1) Sh = 0; 2) 0.34; 3) 1.18.

the slot as compared with the jet from the profiled nozzle for an identical change in the output orifice.

The velocity of coherent structure convection varied between $0.5u_0$ and $0.7u_0$ along the initial section of three-dimensional jets. However, it did not remain constant across the jet section. In the mixing layer evolving from the nozzle smaller edge, the convective velocity of the coherent structure was considerably smaller in comparison with the convective velocity in the mixing layer evolving from the larger edge of the nozzle, where it was close to the convective velocity on the jet axis.

In addition, the features of spatial structure formation and development for three-dimensional turbulent jets were investigated on the basis of the transverse distributions of the characteristic flow parameters. Typical spatial patterns for one section are represented in Fig. 3.

These data also indicate the substantial influence of the initial escape conditions on the formation of both the average and the fluctuation fields of three-dimensional jets. Under identical aspect ratios of the output orifices the spatial effects are more clearly manifest in the jet from the slot with sharp edges as compared with jets from the profiled nozzle.

Displacement of the maximal values of the velocity from the flow axis to the short side of the hole is already noticeable at a short distance from the output section in the jet issuing from the slot, i.e., even in this flow domain secondary currents take place. Under these initial conditions the tendency to an increase in the transverse (parallel to the smaller jet axis) scale of the coherent structure (see Fig. 3c) is manifest to a greater extent.

Analogous three-dimensional flow patterns were obtained for a number of sections in the transition portion of the three-dimensional jets under investigation (for $\bar{x} \geqslant 15$). The spatial effects in this flow section were naturally manifested to a lesser degree because of the intensive jet broadening in the plane of symmetry parallel to the smaller edges of the nozzle, and the equal-velocities and equal-correlations tend to take an almost circular form with distance from the nozzle.

Exactly as for plane and circular jets [8], the presence of coherent structures in the initial section of three-dimensional jets makes them responsive to the action of a different kind of periodic, and particularly acoustic, perturbation.

In the present experiment, a sound field irradiated three-dimensional jets in the transverse direction, perpendicularly to the small sides of the nozzle output orifices.

The frequency characteristic of the dynamics used for this assured a strictly constant sound pressure level on the order of 113 dB in the whole frequency band under consideration.

To increase the difference between the noise level of the jets under investigation and the level of the acting sound field and thereby to increase the effect of the sound action, the escape velocity of the three-dimensional jets was reduced to 20 m/sec in this stage of the investigations. Distributions of the mean and fluctuation velocities along three-dimensional jets were obtained for this escape velocity with and without a sound field present.

The experimental data obtained are in complete correspondence with analogous results for plane and axisymmetric jets [8]. When the jet was formed in a sound field of a low frequency (Sh $\approx$ 0.2-0.6) close to the value of the large-scale coherent structure frequencies, intensification of the turbulent exchange and more rapid damping of the mean velocity along the transition flow section were observed in all the three-dimensional jets under consideration (Fig. 4) as compared with the jets that were not irradiated. Attenuation of turbulence along the initial and transition section axis and an increase in the long-range of the jet were observed at higher acoustic field frequencies (Sh $\approx$ 1-5).

NOTATION

l, h, $\lambda = l/h$, length, width, and aspect ratio of the nozzle output section; z, y, z, coordinate axes; $\bar{x} = x/h$, $\bar{y} = y/h$, $\bar{z} = z/h$, relative coordinates; u_0, velocity at the center of the nozzle output section; u_c, velocity on the jet axis; $\bar{u}_c = u_c/u_0$; $\bar{u} = u/u_0$, relative mean velocity; $\varepsilon = \sqrt{\overline{u'^2}}/u_0$, intensity of longitudinal velocity fluctuations; $\varepsilon_f = \sqrt{\overline{u'^2_f}}/u_0$, intensity of the longitudinal velocity fluctuations in the one-third octave frequency band; $L = 20\log(\varepsilon_f/\varepsilon)$, relative level of rms velocity fluctuations in the one-third octave frequency band; f, the frequency; Sh = fh/u_0, Strouhal number; $R^f = \overline{u'_f(x_1, y_1, z_1)u'_f(x_2, y_2, z_2)} / \sqrt{\overline{u'^2_f}(x_1, y_1, z_1)}\sqrt{\overline{u'^2_f}(x_2, y_2, z_2)}$, spatial correlation coefficient between the longitudinal velocity fluctuations in the one-third octave frequency band.

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