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DISTURBANCE CONVECTION VELOCITY IN TURBULENT JETS UNDER AEROACOUSTIC EXCITATION

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The velocity of propagation of toroidal and oblique vortices formed in subsonic and supersonic turbulent jets under longitudinal internal and transverse external excitation by finite-amplitude saw-tooth acoustic waves is studied experimentally. It is demonstrated that the convection velocity of vortices is not constant, and the character of its variation depends on the vortex shape.

Key words: *turbulent jets, vortices, acoustic excitation.*

Convection of disturbances is an important characteristic of mixing in turbulent jets. The character of mixing is largely determined by the convection velocity. The change in the mixing zone thickness is caused by the ambient medium set into motion, in particular, vortices or their coalescence [1]. Large vortices formed under aeroacoustic excitation being assumed to avoid participation in coalescence processes, the intensity of the mixing process is determined by the degree of involvement of the ambient medium into motion by vortices [2]. The disturbance convection velocity is also important for determining the frequency of the high-intensity discrete tone emitted by supersonic jets in off-design flow regimes, including those in real conditions. Such radiation, which is a finite-amplitude saw-tooth acoustic wave, can lead to fatigue failure of the structure of flying vehicles [3, 4]. Numerous investigations show that the velocity of vortex propagation in undisturbed jets and in jets subjected to acoustic excitation varies in a wide range from $\approx 0.5U_0$ to $\approx 0.8U_0$ (U_0 is the flow velocity at the nozzle exit) [3, 5]. Apparently, these differences in convection velocity are caused by the shape of vortices and by the features of acoustic excitation. The objective of the present work is to determine the effect of the shape of rather large vortices arising in turbulent jets under longitudinal internal and transverse external acoustic excitation on the vortex-propagation velocity. Such vortices arising in turbulent jets under aeroacoustic interaction, in particular, under the action of finite-amplitude saw-tooth acoustic waves, form a model that can be readily used to study origination and evolution of disturbances in jets and to determine the role of these disturbances in turbulent mixing and noise radiation.

The experiments were performed in a large choked chamber based at the Department of the Central Aerohydrodynamic Institute. The tests were conducted with cold subsonic air jets ($\bar{P}_0 = 1.4$–1.7 and nozzle-exit diameter $d = 20$–60 mm), underexpanded supersonic jets exhausting from converging nozzles ($\bar{P}_0 = 1.9$–3.7 and $d = 20$–60 mm), and supersonic jets exhausting from converging-diverging nozzles ($\mathrm{M} = 2$, $\bar{P}_0 = 6.2$–15.6, and $d = 20$ mm). Here $\bar{P}_0 = P_0/P_a$ is the pressure difference in the nozzle, P_0 is the total pressure in the stilling chamber, P_a is the ambient pressure, and M is the design Mach number of the nozzle. Gas-jet Hartmann generators with a frequency $f = 4$–10 kHz were used as a source of sound. In the case of longitudinal internal acoustic excitation, the generator was placed into the settling chamber, so that the necessary total pressure in the chamber was ensured by supporting a pressure difference in the generator corresponding to the operation regime of the latter. The acoustic pressure at the nozzle edge was 160–165 dB, depending on the excitation frequency. In the case of transverse external excitation, the sound generator was located at different distances from the nozzle edge. In some

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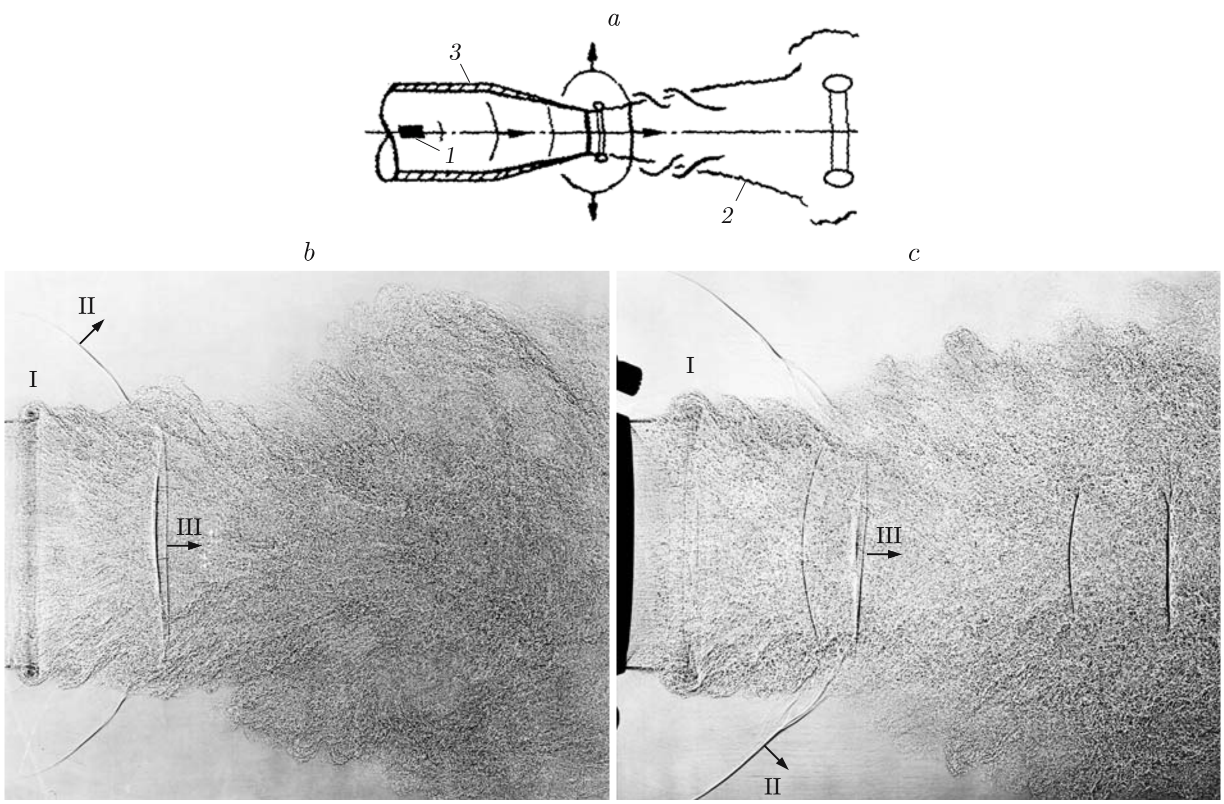

Fig. 1. Schematic of the experiment (a) and shadowgraphs of a turbulent jet (b and c) under longitudinal internal acoustic excitation: (a) Hartmann generator (1), jet (2), and nozzle (3); (b) subcritical flow regime ($\bar{P}_0 = 1.4$ and $f = 1.6$ kHz); (c) supercritical flow regime ($\bar{P}_0 = 2.5$ and $f = 1.6$ kHz); the arrows show the direction of sound propagation; the flowfield consists of the following regions: vortex (I), acoustic wave diffracted on the nozzle edge (II), and acoustic wave in the jet (III).

tests, the generator was placed into an elliptic or parabolic sound baffle. Depending on the frequency, distance from the nozzle edge, and application of the sound baffle under transverse external excitation, the acoustic pressure at the nozzle edge was 155–175 dB.

The experiments were performed with finite-amplitude saw-tooth waves, which generated compact disturbances (vortices). (The influence of the shape of acoustic waves on the shape of the arising disturbances was considered in [6].) The jets, acoustic waves, and vortices were visualized by means of shadowgraphy with a point spark source of light; the size of the luminescent zone was 0.8 mm, and the exposure time was $2 \cdot 10^{-7}$ sec. In the shadowgraphs (see Figs. 1 and 2), the sound-propagation direction in the acoustic-wave front is from the light to the dark band. Thus, all acoustic waves in Figs. 1 and 2 can be readily identified. (In shadowgraphy, the magnification factor depends on the distance from the source of light to the object and to the screen; in our case, it was approximately equal to 1.2.)

Under longitudinal internal excitation of a turbulent jet, the toroidal vortex is formed when the finite-amplitude saw-tooth acoustic wave passes through the phase of the maximum compression in the nozzle-exit section [7]. As the delay is less than 10 μsec, it may be neglected in calculating the convection velocity of the vortex. Application of saw-tooth acoustic waves in determining the vortex-propagation velocity allows us to use the fact that the acoustic wave generating the vortex is visible in the shadowgraphs; hence, the velocity scale is known (see Fig. 1). From the ratio of the distances covered by the vortex (vortex center) I and by the acoustic wave diffracted on the nozzle edge II, we can find the velocity of vortex motion U_c. The velocity of jet exhaustion U_0 can be found from the fact that the velocity of the acoustic wave in the jet III, determined in a similar manner, consists of the jet velocity and the velocity of sound in the jet. The velocity of sound in the jet is determined from gas-dynamic tables, based on the known pressure difference in the nozzle. The velocity of the system of vortices can also be

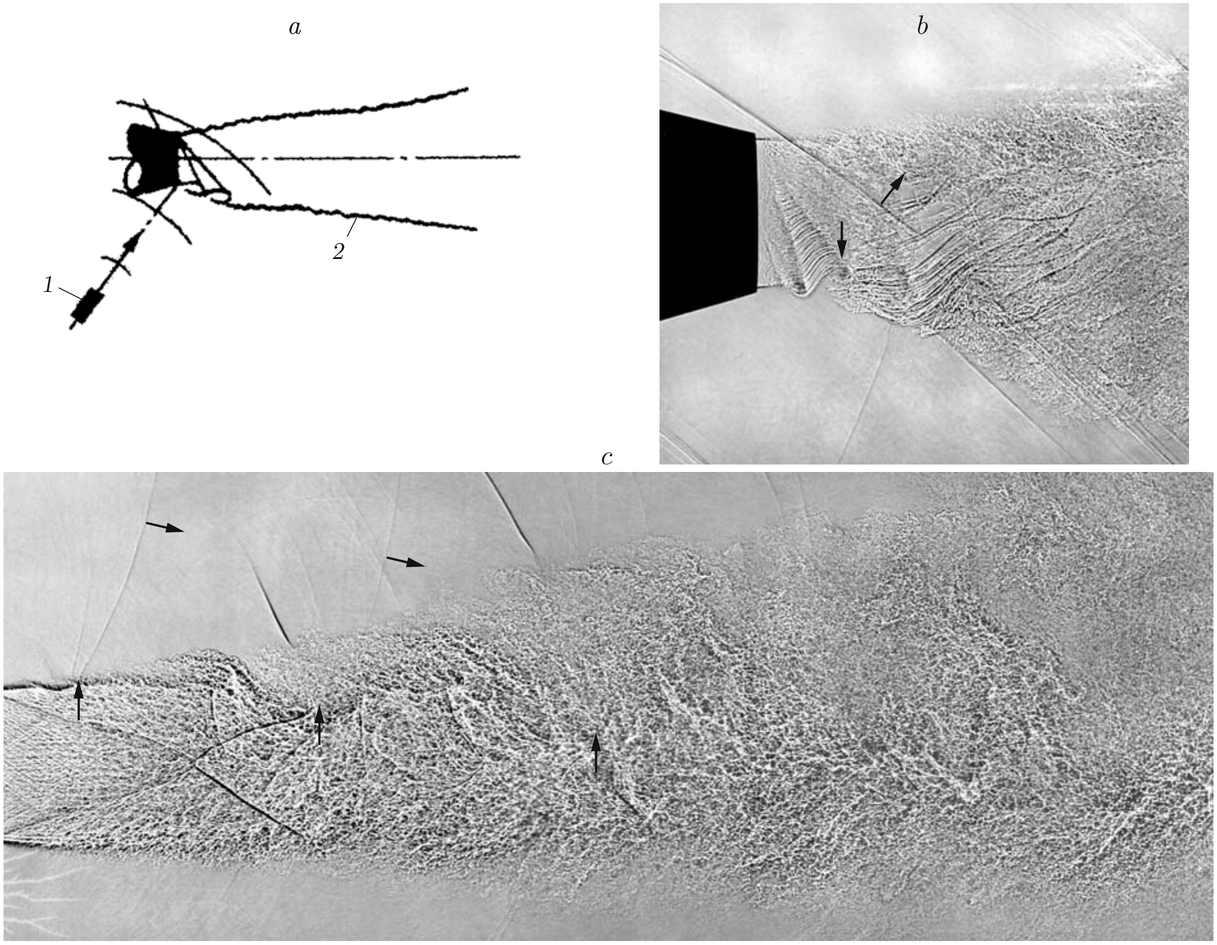

Fig. 2. Schematic of the experiment (a) and shadowgraphs of a turbulent jet (b and c) under transverse external acoustic excitation: (b) subcritical flow regime ($\bar{P}_0 = 1.4$ and $f = 8.0$ kHz); (c) supercritical flow regime (M $= 2.0$, $\bar{P}_0 = 6.2$, and $f = 8.0$ kHz); the remaining notation the same as in Fig. 1.

found by the formula $U_c \approx 0.8\Lambda f$, where Λ is the distance between the vortices, f is the frequency of acoustic excitation, and the numerical coefficient takes into account the increase in Λ during the time the shadowgraphs are taken. The results interpreted from the shadowgraphs obtained in subcritical and supercritical flow regimes show that the convection velocity of the toroidal vortex is not constant and there is a flow portion where the vortex moves with acceleration (Fig. 3). The convection velocity of the vortex in the initial jet segment of length smaller than $(0.5–1.0)d$ was calculated on the basis of the position of the acoustic wave diffracted on the nozzle edge and the vortex formed. At a distance from the nozzle greater than $(1–2)d$, the convection velocity was calculated from the distance between the vortices (Fig. 3a). Figure 3 also shows the root-mean-square values of convection velocity and measurement uncertainties. The convection velocity of the toroidal vortex is $\approx 0.5U_0$ at the initial part of motion and then increases to $(0.7–0.8)U_0$.

Under transverse external acoustic excitation, like in the case with longitudinal internal excitation, the disturbance arises in the phase of the maximum compression of the jet at the nozzle edge, and the delay may also be neglected. The displacement of the oblique vortex is understood as the displacement of its characteristic part shown by the arrows in Fig. 2. The shadowgraphs of oblique vortices formed under transverse excitation of turbulent jets by finite-amplitude saw-tooth waves were processed in the same manner as those obtained under longitudinal acoustic excitation. The position of the acoustic-wave front with respect to the irradiated nozzle edge defines the velocity scale in the case considered here as well. The test results show that the processes of disturbance propagation in the cases with two types of excitation considered are essentially different: the convection velocity

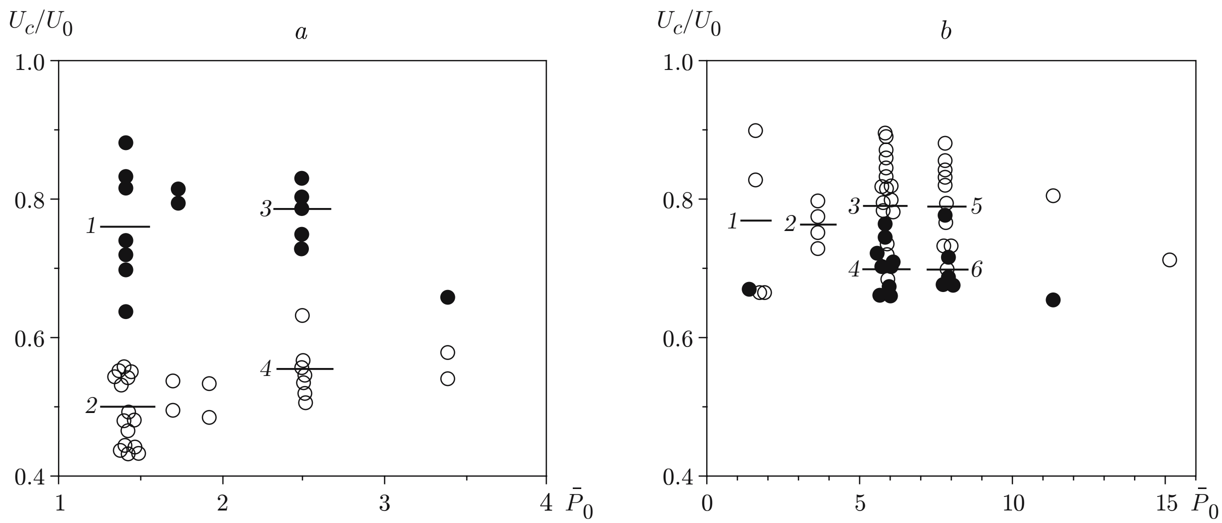

Fig. 3. Convection velocity determined on the basis of the velocity of sound and the position of the first vortex (open points) and on the basis of the distance between the vortices (filled points): (a) toroidal vortices with $\bar{U}_c/U_0 = 0.77 \pm 0.07$ (1), 0.5 ± 0.05 (2), 0.79 ± 0.04 (3), and 0.55 ± 0.04 (4); (b) oblique vortices with $\bar{U}_c/U_0 = 0.77 \pm 0.1$ (1), 0.76 ± 0.02 (2), 0.79 ± 0.04 (3), 0.7 ± 0.02 (4), 0.79 ± 0.05 (5), and 0.7 ± 0.05 (6).

of oblique vortices reaches the highest value ($\approx 0.8U_0$) at the initial part of motion and decreases to $\approx 0.7U_0$ as the vortex moves away from the nozzle edge (Fig. 3b). A possible reason is the different degrees of involvement of the toroidal and oblique vortices into the mean flow: the toroidal vortex originates and evolves at the periphery of the mixing zone, gradually becomes entrained into the mean flow, and increases in size, while the mean flow is involved into the very beginning of origination of the oblique vortex. The test results, in particular, show that the difficulties inherent in attempts made to obtain emission of Mach waves from the toroidal vortex under longitudinal internal excitation and supersonic velocities of the jet [7] are caused by a moderate value of convection velocity of the toroidal vortex at the initial part of motion and by the existence of a limiting velocity of exhaustion of a cold air jet. It should be noted that the convection velocity of the disturbance arising under the action of a discrete tone emitted by the supersonic jet in off-design flow regimes is not a constant quantity, as it is commonly assumed in existing methods for calculating the discrete tone frequency [3]. Another, even more important outcome of this work is the observed phenomenon of acceleration of the toroidal vortex and deceleration of the oblique vortex: the motion of large eddies that either rapidly grow or are rapidly accelerated (decelerated) is an extremely useful model of noise sources in the jet, which allows modeling the most intense sources of sound [8].

The study performed showed that the process of propagation of disturbances under aeroacoustic interaction strongly depends on the disturbance shape: the convection velocities of toroidal and oblique vortices are different. A fairly rapid acceleration of toroidal vortices formed under longitudinal internal acoustic excitation and deceleration (at the initial part of motion) of oblique vortices formed under external acoustic excitation are observed.

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