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# OCCURRENCE AND DEVELOPMENT OF VORTICES IN TURBULENT JETS UNDER THE EFFECT OF SAWTOOTH SOUND WAVES OF FINITE AMPLITUDE

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*Consideration is given to the formation of vortices in turbulent jets under the effect of sawtooth sound waves of finite amplitude in the case of internal longitudinal acoustic action. The convection velocity and the rate of rise of the disturbances are determined. It is shown that the transverse dimensions of the disturbances increase linearly on the initial portion of the flow.*

1. In connection with the role of vortices in the processes of mixing and emission of sound by turbulent jets, which is important in the opinion of many researchers (see, for example, [1]), of particular interest is the process of formation of vortices in undisturbed turbulent jets and in jets which are under the effect of sound and also the possibility of influencing this process. In practice, in the case of acoustic action on the jets use is usually made of monochromatic sound waves of a comparatively small amplitude. In some works [2, 3], the influence of multifrequency acoustic action on the processes of mixing and emission of noise by turbulent jets is investigated. In these works, the influence of the shape of a sound wave on these processes is essentially studied since it is precisely the spectrum of action that determines the shape of the sound wave. The subject matter of the present work is the formation of vortices in subsonic and supersonic turbulent jets under the effect of sawtooth waves of finite amplitude. Such waves occur in practice, for example, in the case of emission of the so-called discrete tone by noncalculated supersonic jets, and such an action on the jets can be realized quite easily. The use of finite-amplitude waves in experimental investigations makes it possible to study the process of interaction of sound with the jets in greater detail, since in shadow photographs one can see both the vortices that are the main object of investigation in this case and the sound waves generating them. In the present work, we consider the initial stage of the process of formation of vortices in subsonic and supersonic turbulent jets in the case of internal longitudinal acoustic action.

2. The experiments were conducted in a large anechoic acoustic chamber of the Acoustic Department of the Central Aerohydrodynamics Institute with isothermal air jets flowing out of subsonic convergent nozzles with a diameter of the outlet cross section of the nozzle of 60 mm (the velocity of outflow was $U$ = 120–460 m/sec). Hartmann gas-jet oscillators with frequencies of 1 to 1.6 kHz were used as the sources of sound. In the case of internal longitudinal acoustic action the emitter was located in the forechamber of the nozzle (the forechamber diameter was 690 mm) and the pressure difference required for the normal operation of the emitter was set on it; the sound-pressure level (SPL) on the nozzle edge attained a value of 160–170 dB depending on the frequency of the action. The spectrum of the emitted sound waves is rich in higher harmonics, and they represent sawtooth waves of finite amplitude. To visualize the process of interaction of sound with a jet we employed the direct shadow method with a spark point light source with a time of exposure of 0.3 μsec. The direction of propagation of the sound waves in the shadow photographs corresponds to the direction from the light strip to a dark one in the picture of the sound-wave front; therefore, one can easily identify all the sound waves in the given photographs. In some photographs, the direction of propagation of sound is shown by arrows.

3. In the case of the internal longitudinal action of a sawtooth sound wave of finite amplitude on a jet, a toroidal vortex is formed when the phase of maximum compression passes through the outlet cross section of the nozzle (Fig. 1). In the photograph, the presence of the front of the sound wave, which prescribes the velocity scale, in the environment makes it possible to determine with a high degree of accuracy the velocity of convection of the vor-

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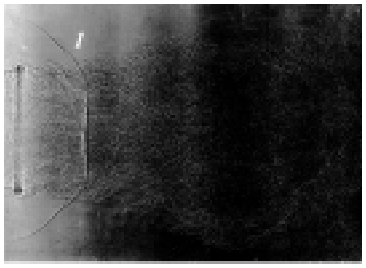

Fig. 1. Interaction of sound with a subsonic jet [$\bar{p}_0 = 1.2$; 1) sound wave].

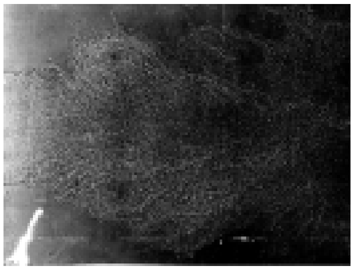

Fig. 2. Occurrence of vortices in a subsonic jet at the frequency of intrinsic instability of the shearing layer ($\bar{p}_0 = 1.2$).

tex in this time interval (the position of the sound-wave front in the potential core of the jet, i.e., in the cone of constant velocities, makes it also possible to calculate the jet velocity in the core, since the velocity of propagation of the sound-wave front is made up of the velocity of the flow and the velocity of sound in the flow). In the photograph, the velocity of the flow is 163 m/sec and the velocity of convection of the vortex is 95 m/sec, i.e., it amounts to 58% of the velocity of the jet in the outlet cross section of the nozzle. The formation of vortices at the frequency of the external action leads to the disturbance of the shearing layer at the eigenfrequency of instability of the shearing layer

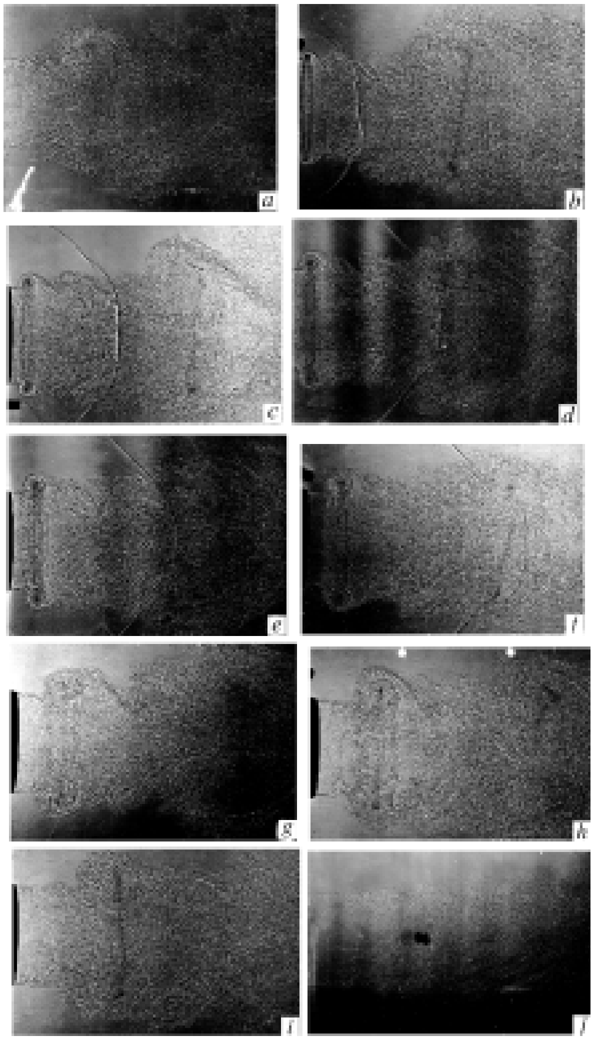

Fig. 3. Occurrence and development of a vortex in a subsonic turbulent jet under the effect of sound ($\bar{p}_0 = 1.4$) (*a*–*i*) and the undisturbed jet (*j*).

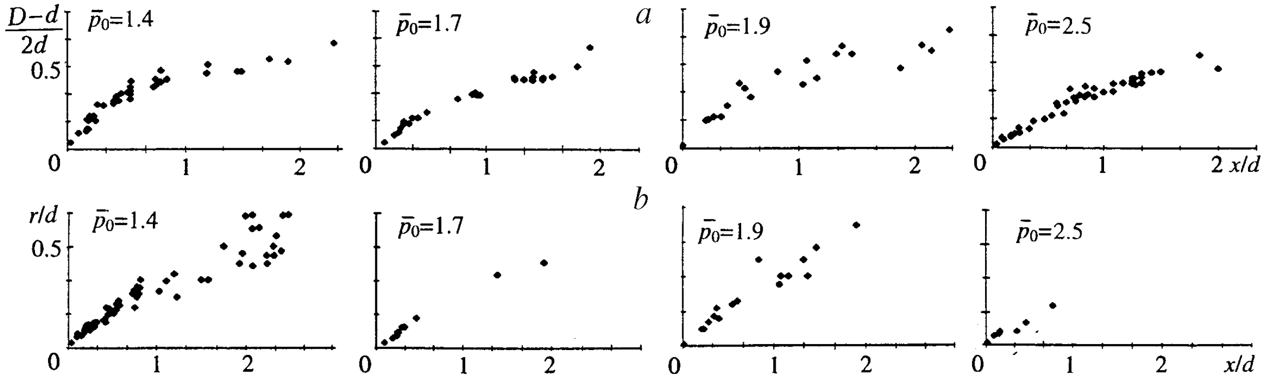

Fig. 4. Width of the mixing zone of the jet (a) and radius of the toroidal vortex (b) vs. distance along the jet axis.

(Fig. 2); this frequency can easily be determined from the found convection velocity: it is 9.4 kHz in the given photograph.

It turns out to be possible to investigate the process of development of a vortex with time owing to a rather high stability of the process of interaction of sound with the jet. Arranging the shadow photographs obtained in the order which is prescribed by the position of the sound wave or the vortex formed under the effect of sound in the photographs (the time interval between the photographs is about 50–100 μsec), we can obtain a rather detailed picture of occurrence and evolution of a vortex. Figure 3 gives shadow photographs of a subsonic jet ($\bar{p}_0$ = 1.4, $U$ = 230 m/sec) in the case of internal longitudinal acoustic action with a frequency of 1.6 kHz. The sound-pressure level recorded by the microphone near the edge of the nozzle in the plane of its outlet cross section is 150 dB, but this is the sound-pressure level in a diffracted wave, while the evaluation of the sound-pressure level in the outlet cross section of the nozzle gives a value of 165 dB. (In some of the given photographs, the jet can simultaneously be under external acoustic action but, as was shown in [4, 5], the sound with an intensity of up to 170 dB attained in the experiments conducted has no appreciable effect on the already formed vortices.) Similar shadow photographs showing the picture of formulation of vortices have also been obtained in transonic and supersonic regimes of outflow ($\bar{p}_0$ = 1.7, 1.9, and 2.5). The dependence of the quantity characterizing the width of the mixing zone of the jet and of the vortex radius (Fig. 4) on the distance along the jet for the investigated values of the pressure difference on the jet shows that on the initial portion of the flow the transverse dimension of disturbances increases linearly under the effect of high-intensity sound. It would appear reasonable that for lower values of the level of acoustic action the character of change in the disturbances in the mixing layer will not change. Thus, the substantially nonlinear process of interaction of sound with the mixing layer which causes it to curl into vortices is confined to the flow region adjacent to the nozzle section, while the disturbances that occurred in the investigated mixing layers develop linearly.

It is clear that the indicated disturbances yield the picture of the jet boundary that could also be obtained in the case of measurement of the averaged parameters of the jet or increase in the time of exposure during the photographing: for the investigated values of the parameters of the jets, the jet boundary is straight on a portion of about one caliber when the size of the toroidal vortex increases linearly; as the distance from the plane of the outlet cross section of the nozzle increases further, the rate of rise of the transverse dimensions of the jet decreases.

The initial stages of formation of vortices for subsonic velocities of outflow of the jet and at supercritical pressure differences on the jet in the case of internal longitudinal acoustic action are similar in many respects but at supercritical pressure differences the toroidal vortex loses its shape rapidly under the effect of significant pressure gradients in the mixing layer; at the same time, it preserves its identity at a large distance from the outlet cross section of the nozzle.

## CONCLUSIONS

1. Investigation of the occurrence and development of vorticity in turbulent jets under the effect of sound of high intensity has shown that the transverse dimensions of the disturbances that occurred change linearly.

2. The presence of the sound-wave front in shadow photographs makes it possible to determine with a high degree of accuracy the velocity of propagation of the disturbances in turbulent jets which are under the effect of sound.

3. Excitation of the mixing layer of the jet under the effect of sound of high intensity and in passage of the toroidal vortex makes it possible to determine the frequency of intrinsic instability of the shearing layer from the shadow photographs.

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## NOTATION

$d$, nozzle diameter, mm; $D$, width of the jet in a certain cross section, mm; $\bar{p}_0$, total pressure in the jet referred to atmospheric pressure; $r$, vortex radius, mm; SPL, sound-pressure level, dB; $U$, velocity of the jet in the outlet cross section of the nozzle, m/sec; $x$, distance along the jet axis, mm.

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