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Disturbance Generation in Supersonic Jets Under Acoustic Excitation

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Experimental results are presented on the interaction of saw-toothed high-intensity sound waves [sound pressure level (SPL) = 160–170 dB] with an axisymmetrical supersonic air jet. The flow and sound waves were visualized by the direct shadowgraph method using a spark light source with exposure time of 2×10^{-7} s. It is shown that disturbance increase increment in a supersonic jet under external acoustic excitation depends on the angle of incidence of the sound wave to the jet boundary. The most intensive increase in jet disturbances occurs at an oblique sound incidence when the sound phase velocity along the boundary approaches the disturbance propagation velocity. For sufficiently intense jet disturbances, a shock wave formation induced by and moving with these disturbances may arise. Sound interaction with a supersonic jet takes place within a small flow zone near the nozzle exit; disturbances already developed are not noticeably affected by the sound intensity of 170 dB reached in the experiment.

Introduction

An experimental investigation was carried out to study the nature of sound interaction with supersonic jets. Sound interaction with jets has attracted the attention of investigators for a long time, but usually only for subsonic jets. Relatively few papers are devoted to sound interaction with supersonic jets, apparently because much higher sound excitation levels are required to affect their aerodynamic performance to any significant extent, and this involves certain practical difficulties. In Ref. 1, and in a number of similar papers, the influence of the discrete tone of a supersonic jet on its expansion and attenuation was investigated at off-design flow regimes. In Ref. 2, sound interaction with a supersonic jet was studied, perhaps for the first time, using an independent external sound source of high intensity. It was shown there that with increased acoustic excitation level the jet expanded and attenuated faster. It is shown in Ref. 3 that for the aerodynamics of a supersonic jet to be changed significantly the intensity of the sound wave at the nozzle lip should amount at least to 0.1–0.2% of the jet total pressure. Under the action of sufficiently high-intensity sound at normal incidence to the supersonic jet boundary, disturbances whose space scales depend on the jet velocity and frequency appear. These disturbances move along the excited jet boundary, increasing in size, and radiate Mach waves into the ambient space at the external excitation frequency.

The purpose of this paper is to investigate peculiarities of the formation and initial stages of development of supersonic jet disturbances under high-intensity sound excitation. Use was made of two types of acoustic excitation: external lateral excitation produced by a Hartman generator (HG) placed in free space or in a parabolic or elliptic reflector to increase acoustic excitation, and internal longitudinal excitation produced by the HG functioning in the settling chamber. A more detailed description of the experimental installation and techniques is given in Ref. 3. The main feature of the method used is acoustic excitation at sufficiently high intensity by saw-toothed sound waves [sound pressure level (SPL) = 160–170 dB] which can be visualized like the jet itself using the shadowgraph technique. In the experiment, a spark source with the size of a luminous body of 0.8 mm, exposure time of 2×10^{-7}s, and discharge energy of 2 J was used.

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Results and Discussion

It is known that the angle of incidence of the sound wave has only a small effect on subsonic jet sound excitation.[4] At supersonic jet velocities, there exists the possibility of coincidence of the wave number of the disturbed motion with the wave number of the incident sound wave or with its projection onto the disturbance propagation direction, which is in principle unattainable for subsonic jets. The investigation of the influence of the sound wave angle of incidence on a supersonic jet was carried out with a supersonic air jet issuing from a conical supersonic nozzle designed for $M = 2.0$ with exit diameter $d = 20$ mm and at static pressure ratios $n = 0.8$ and 1.0. As the sound source, HG was used ($f = 10$ kHz, acoustic output 0.4 kW). Its central core moved along an arc of 120 mm radius, with its center on the nozzle lip nearest to the sound generator. The angle α between the jet flow direction and the direction to the sound source varied from 30 to 160 deg. The disturbance increase increment δ in the supersonic jet under acoustic excitation was estimated from shadowgraphs. This characteristic of the interaction phenomenon was chosen to emphasize that it has a determinate rather than random character. The disturbance increase increment was evaluated

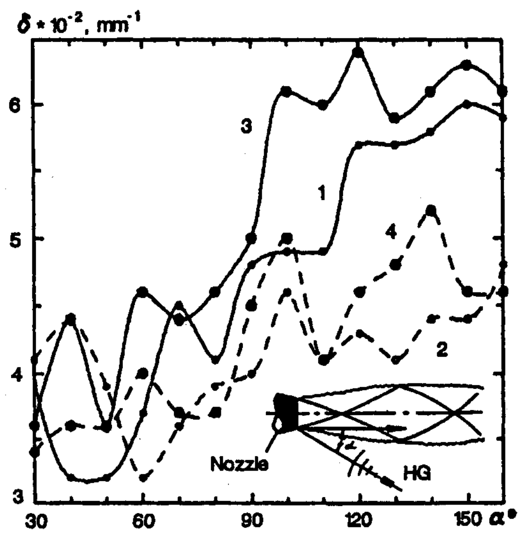
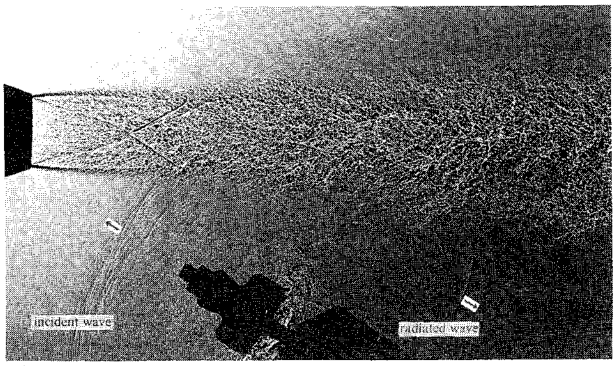


Fig. 1 Dependence on sound incidence angle α of the disturbance increase increment δ on jet boundaries near to [1) $n = 0.8$, 3) $n = 1.0$] and far from [2) $n = 0.8$, 4) $n = 1.0$] HG.

from a series of photographs taken at random moments of time and disposed in a definite order depending on the sound wave front position. The possibility of such a consideration is based on observations that a sufficiently high degree of stability of the interaction phenomenon existed. In the initial flow adjacent to the nozzle, the cross disturbance size appears to grow exponentially, in general agreement with theoretical ideas of instability in a supersonic shear layer for the relative Mach number $M < 2\sqrt{2}$ (Ref. 5).

The dependence on sound incidence angle of the disturbance increase increment on the jet boundaries that are near to and far from HG shows (Fig. 1) that for oblique sound incidence on a jet boundary with the phase velocity of sound propagation along the jet boundary in the initial part of the



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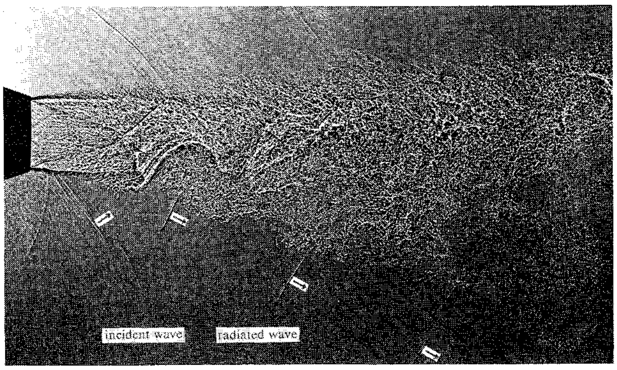


b)

Fig. 2 Supersonic jet shadowgraphs of sound incidences on jet boundary: a) head on, $\alpha = 30$ deg and b) oblique, $\alpha = 160$ deg; $n = 0.8$.

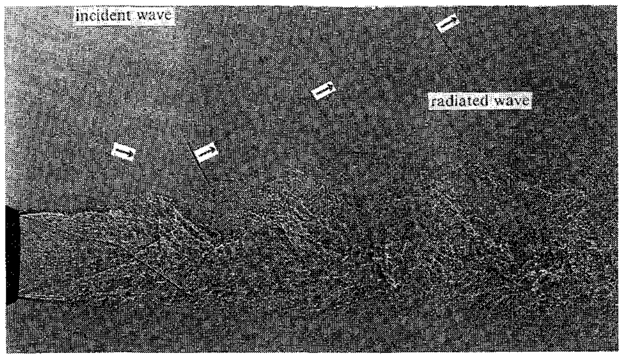


Fig. 3 Unsteady shock-wave formation in supersonic jet under sound excitation: $M = 2.0$, $n = 0.8$, $f = 10$ kHz, SPL = 160 dB, and $\alpha = 160$ deg.

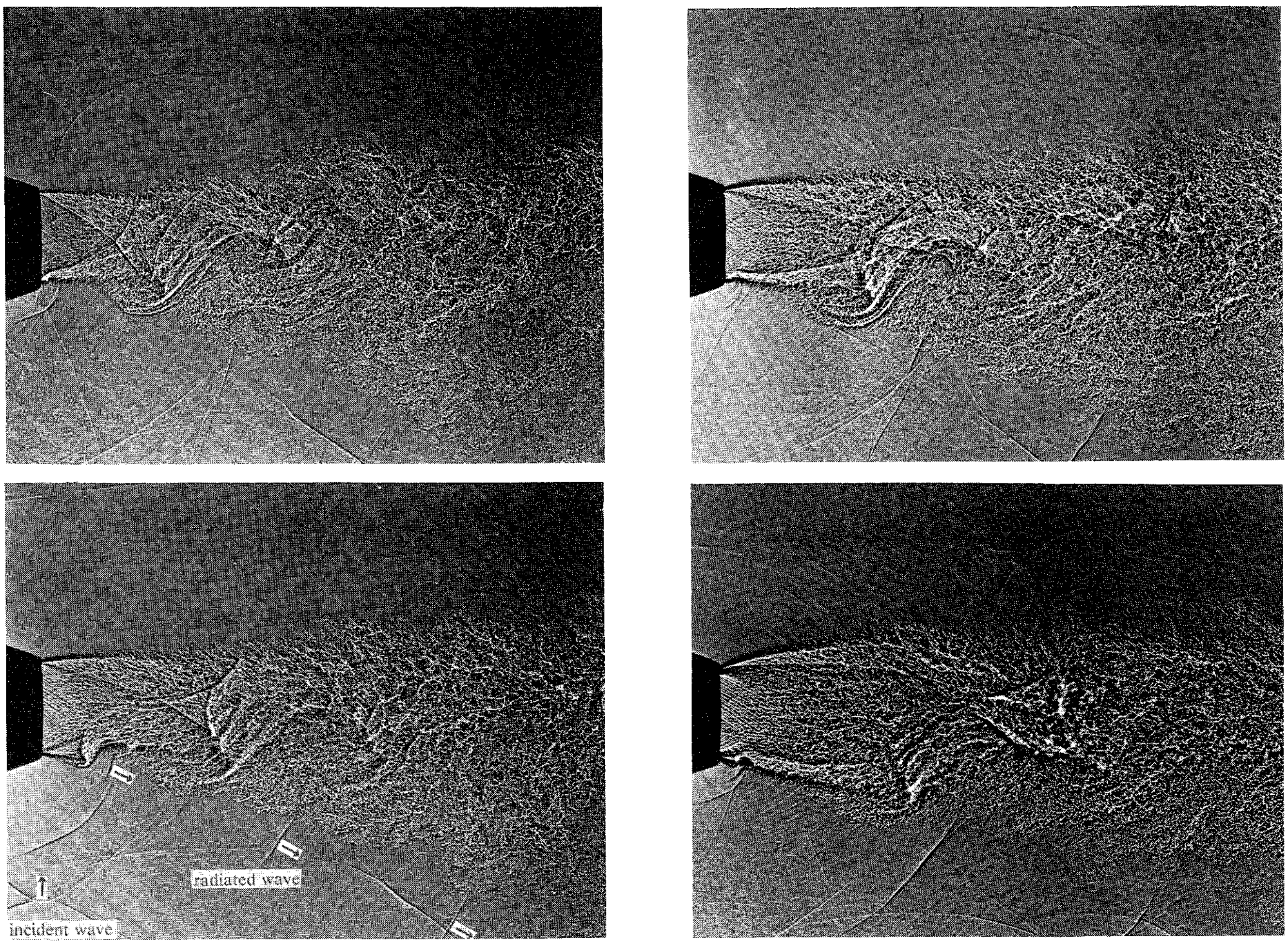


Fig. 4a Initial stage of disturbance generation in a supersonic jet under sound excitation: $M = 2.0$, $\alpha = 90$ deg; and $n = 0.5$, 0.8, 1.0, and 1.5.

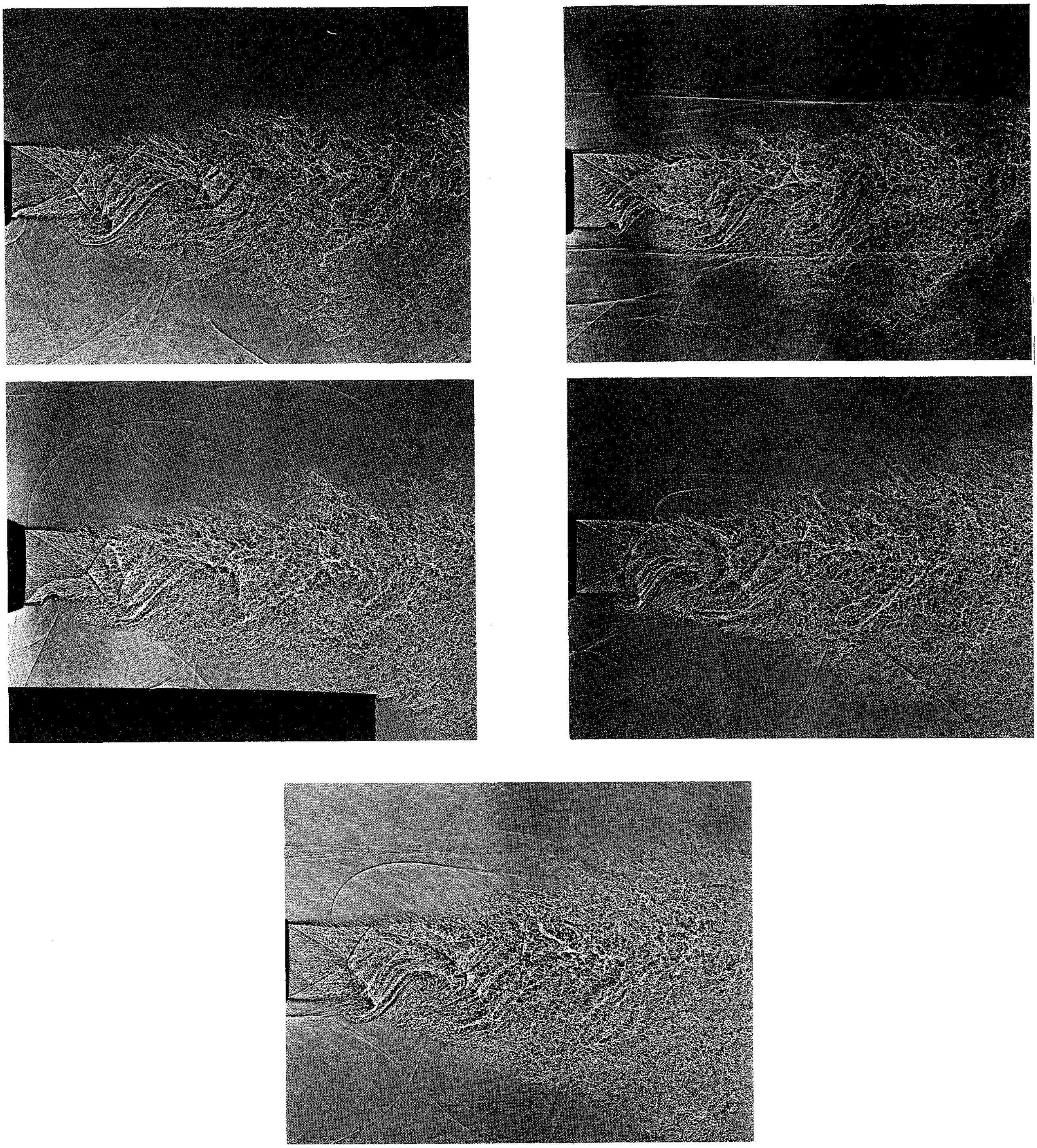


Fig. 4b High-intensity sound-supersonic jet interaction: $M = 2.0$, $n = 0.5$, $\alpha = 90$ deg.

flow close to the jet disturbance propagation velocity, the disturbance increase on the excited boundary is most intensive. The experiments carried out seem to show the possibility of direct interaction between the sound and disturbance generated by it: in the case of oblique sound incidence on a supersonic jet, the sound wave energy is transferred to the vortex motion. This treatment of the results obtained seems to be quite acceptable and natural, but in general it is not the only possible explanation, and the sound-supersonic flow interaction mechanism remains unclear in many aspects. As an example, Fig. 2 shows shadowgraphs taken in these experiments of some patterns of a supersonic jet with head-on and oblique sound incidences on its boundary. Sound intensity at the nozzle lip was measured to be the same (160 dB). All of the sound waves in the shadowgraphs presented in this paper can be easily identified by noting that the propagation direction of any wave corresponds to the direction from a light line to a dark one in the sound wave front picture (Fig. 2 gives the propagation direction indicated by arrows and labels for the incident sound wave and Mach waves radiated by the jet under acoustic excitation).

In the case of the optimum sound wave angle of incidence to the supersonic jet boundary, when large-scale disturbances of the greatest magnitude arise, initiation of a shock-wave pattern induced by these disturbances is possible (Fig. 3). These shocks exist along with the steady shock-wave formation that is characteristic of supersonic jets in off-design flow conditions. In contrast to it, however, as follows from the consideration of the development of this phenomenon using the series of photographs, they moved together with the disturbances induced by sound excitation. The unsteady shock wave pattern in an excited supersonic jet seems to be associated with large-scale disturbances streamlined by a flow in its relative motion. Apparently, this phenomenon is similar to that observed in a flow over rather large solid inclusions transferred by supersonic flows. The disturbance convection velocity can be easily found from the shadowgraphs: the ratio of disturbance convection velocity to the speed of sound is equal to that of the distances covered by the disturbance and the sound wave from the nozzle lip. This determination of convection velocity is based on the experimental fact that the disturbance arises within the jet at the nozzle edge when the zone of maximum sound wave compression passes. The convection velocity obtained in such a way in the initial flow system is 0.6–0.75 of the nozzle exit jet velocity. For sufficiently intense disturbances by sound, the steady shock wave pattern of the supersonic jet can be destroyed.

A more detailed understanding of the mechanism of generation of supersonic jet disturbances by acoustic excitation can be gained by exciting the jet with high-intensity sound. In our experiments, SPL = 172 dB was achieved by using sound reflectors (elliptic and parabolic) at whose focus HG was placed. Figure 4a shows the initial stage of disturbance generation in supersonic air jets ($M = 2.0$; $d = 20$ mm; and $n = 0.5$, 0.8, 1.0, and 1.5). The high-intensity sound interaction with the supersonic jet is characterized by a hollow formed in the mixing layer as the zone of maximum acoustic compression passes through the nozzle exit. Subsequently this disturbance develops into a vortex formation of complex shape. The initial stage of disturbance generation is nearly independent of jet pressure (both total and static). At the sound excitation intensity obtained, the disturbance affects not only the mixing layer but also the flow core. There are distinct longitudinal vortices on sound-excited disturbances which, in our view, can be identified as Gortler-Taylor vortices. The significant extent of these vortices revealed in the acoustic excitation is indicative of their stability and the important role in the formation of the mixing layer of supersonic jets. The shadowgraphs show the incident sound waves, the wave reflected from the nozzle, Mach waves radiated by disturbances induced by acoustic excitation on the excited jet side, and sound waves radiated from the end of the first cell of the shock wave pattern. For the flow with static-pressure ratio $n = 0.5$, the interaction of high-intensity sound with the supersonic jet is shown in the series of photographs in Fig. 4b.

If HG is displaced from the parabolic reflector focus, one can obtain a sound wave front of complex shape along which the sound intensity varies significantly. The excitation of a supersonic jet by the trapezoidal front sound wave shows that jet disturbances occur at the nozzle lip (Fig. 5). In the case

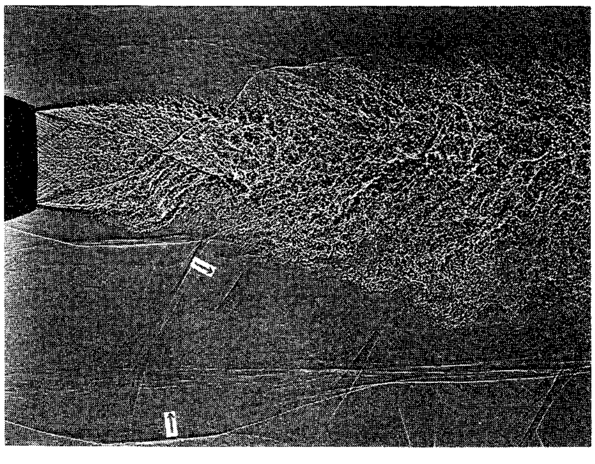
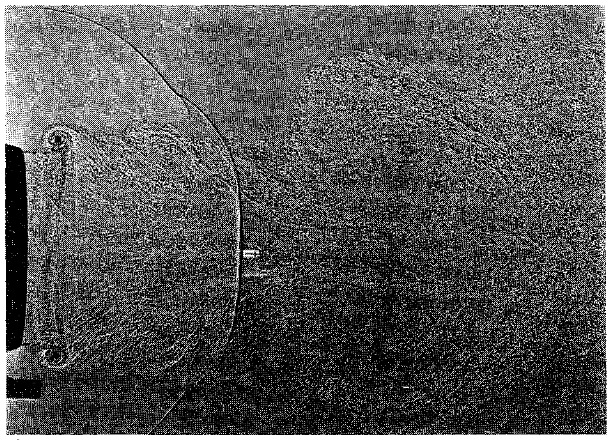


Fig. 5 Trapezoidal sound wave front-supersonic jet interaction: $M = 2.0$, $n = 0.8$.



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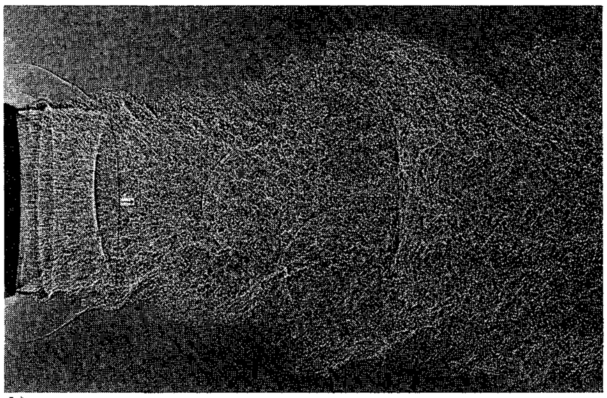

b)

Fig. 6 Initial stage of disturbance generation under longitudinal internal acoustic excitation: a) in a subsonic jet, $\bar{p}_0 = 1.2$ and b) in a supersonic jet, $\bar{p}_0 = 2.5$.

shown in the figure, the sound intensity at the nozzle lip is 15 dB less than that in the center of the sound wave, but it is sound excitation of the flow at the nozzle lip that causes jet disturbances. This follows from consideration of the relative position of the incident sound wave front, the jet disturbance, and the Mach wave radiated by this disturbance. In this case the high-intensity sound in the center of the sound wave front (172 dB) normal to the jet boundary does not affect significantly the jet section subject to its excitation. A systematic investigation of the sound influence on different jet regions under normal sound incidence on the boundary has shown that sound of the intensity attained in our experiments has no direct influence on flow, and that the jet spread is completely governed by intensity and angle of incidence on the nozzle lip. In the experiments, an initial jet section 10 diameters in length was affected by acoustic excitation ($M = 2.0$; $d = 20$ mm; and $n = 0.5$, 0.8, 1.0, 1.5, and 2.0).

If HG is placed into the settling chamber of the nozzle under consideration with the required total pressure provided by an air supply through HG, it is possible to achieve an intensive sound radiation in the settling chamber while maintaining HG pressure ratio required for its normal functioning. The settling chamber should have sufficiently large dimensions, so that the air supply through the HG does not affect the aerodynamic properties of the jet. Such an arrangement enables investigation of the intensive sound-jet interaction under longitudinal internal excitation.

The tests carried out have shown that the initial stage of the disturbance formation at subcritical and investigated supercritical pressure ratios is similar to the toroidal vortex initiation at the nozzle lip at the time the zone of maximum sound wave compression passes through the nozzle exit (Fig. 6). In both cases, the vortex initiation under sound excitation is a short-term process (of the order of several microseconds at the investigated flow velocities) which does not depend on the excitation frequency. A sound-excited vortex develops in different ways in subsonic and supersonic jets: in subsonic jets the vortex retains its shape, increasing in scale at the distance of 3–4 diameters from the nozzle lip, whereas in supersonic jets its shape can vary significantly within a distance of only one diameter. As in the case of external acoustic excitation, supersonic jets under internal longitudinal acoustic excitation and with sufficiently great pressure ratios may contain shocks induced by the mean flow over the vortex and moving together with it. The experiments were carried out by using a convergent nozzle with the exit diameter of 60 mm and with pressure ratios $\bar{p}_0 = 1.2$ and 2.5 at the sound frequency 1.3 kHz.

Conclusion

As a result of investigations of high-intensity sound-supersonic jet interaction it is shown that the disturbance increase increment in a jet under acoustic excitation depends on the angle of the incidence of the sound to the jet boundaries. The most intensive disturbance in a jet takes place when the sound phase velocity on a jet boundary is close to the disturbance propagation velocity. At the optimum sound wave angle of incidence which causes the strongest jet disturbances, or at high sound intensity in a supersonic jet, there can arise a shock-wave formation induced by relative flow over these disturbances and moving together with them. Supersonic jet excitation by a sound wave with a trapezoidal front, obtained by using a parabolic reflector, made it possible to establish that the sound-supersonic jet interaction takes place in the part of the flow near the nozzle lip. Sound of the intensity attained has no noticeable effect on disturbances already formed. This conclusion was confirmed by exciting different parts of the supersonic jet with sound at intensity of 170 dB.

Acknowledgments

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References

[1]Glass, D. R., "Effect of Acoustic Feedback on the Spread and Decay of Supersonic Jets," *AIAA Journal*, Vol. 6, No. 10, 1968, pp. 1890–1897.

[2]Yeryomin, G. I., and Kondratiev, V. I., "Acoustic Effects on a Supersonic Jet Flow and its Noise Spectrum," *Aeroacoustics*, Nauka, Moscow, 1980, pp. 119–123.

[3]Pimshtein, V. G., "On Sound Excitation of Supersonic Jets," *Izvestiya AN SSSR, Mekhanika Zhidkosty i Gasa*, No. 6, 1989, pp. 170–174.

[4]Vlasov, E. V., Ginevsky, A. S., and Kolesnikov, A. V., *Aeroacoustic Interactions*, Mechanical Engineering, Moscow, 1978, p. 123.

[5]Miles, J. W., "On the Disturbed Motion of a Plane Vortex Sheet," *Journal of Fluid Mechanics*, Vol. 4, Sept. 1958, pp. 538–552.