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Technical Notes

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Structure and Noise of a Supersonic Jet Under Internal Acoustic Excitation

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Introduction

THE acoustic excitation of turbulent jets as a method of study and a means of affecting their aerodynamic and acoustic characteristics and coherent structures is the subject of a number of theoretical and experimental investigations. In such works a sinusoidal excitation of small intensity is used, as a rule, and the subject of studies is a subsonic jet. The effect of multifrequency acoustic excitation on subsonic jets was also investigated, and a certain number of works deal with the effect of high-intensity sound on jets.[1] As it is believed, the effect of small-intensity sound on subsonic jets with Reynolds number $Re < 10^5$ can reduce the noise radiation, and in this case the means of acoustic excitation (internal or external) is of no concern. The investigation of the external lateral excitation of the supersonic jet by sawtoothlike sound waves of finite amplitude demonstrated a possibility of overcoming the so-called "Reynolds number barrier," the idea introduced by Crighton, assuming that the jet noise at $Re > 10^5$ can be only amplified under sound excitation,[2] and of reducing the supersonic jet noise.[3] The proper jet shock-wave structure can essentially vary in this case, and appearance of the compact hydrodynamic disturbances can be accompanied by Mach wave radiation at the external excitation frequency, if their convective velocity exceeds the ambient sound velocity.[4] The internal longitudinal excitation of turbulent jets with Reynolds number $Re > 10^5$ leads to increasing the noise radiated by the jet,[5] but at the present time the mechanism of such an effect and its influence on supersonic jet structure remains unclear in many aspects. The purpose of the present work is to investigate the effect of the longitudinal internal high-intensity sound excitation on a cold supersonic air jet structure and noise.

Experimental Facility and Measurement Procedure

The experiments were carried out in a large anechoic chamber of the Acoustic Division of the Central Aerohydrodynamic Institute with unheated air jets issuing from a convergent–divergent nozzle designed for Mach number $M = 2.0$ with exit diameter $d = 30$ mm and at the total pressure in the settling chamber $P = 6.2$ atm. The acoustic excitation was produced by a Hartman generator (HG) with a frequency $f \sim 4$ kHz placed in the settling chamber of 290 mm in diameter coaxially with the nozzle at a distance of 300 mm from its inlet cross section: a sinusoidal sound wave radiated by HG is transformed into a sawtoothlike wave of finite amplitude at such a distance. The setup scheme is shown in Fig. 1 The rms value of sound pressure level (SPL) generated by HG in the free space at such a distance is $\sim$165 dB. The required pressure in the settling chamber was provided by air supply through HG and the pressure ratio, which was required for HG normal functioning, maintained in it. The acoustic near-field structure of jets was investigated with an automatic measurement system controlled by computer. The measurements were carried out in knots of a rectangular coordinate network with a cell dimension $5d \times 5d$ set at a distance of $1d$ from the jet boundary. (The half-angle of opening of the jet was assumed to be 7 deg.) The measurement results were accumulated, deciphered, and summarized in $\frac{1}{3}$-octave frequency bands. A microphone of 4136 type and an analyzer of 2032 type B&K were used in the experiments; the accuracy of the data obtained was ± 1 dB. The acoustic measurement results were presented in the form of lines of equilevel rms values of the sound pressure levels at different values of Helmholtz number ($He = fd/a$, where a is the ambient sound velocity). The supersonic jet structure investigation under acoustic excitation was carried out with flow visualization, using a direct shadowgraph method (exhibition time 2×10^{-7} s, illuminating body dimension 0.7 mm). The sound propagation direction of any wave corresponds to the direction from a light line to a dark one in the sound wave front picture and is shown by arrows in the shadow pictures. In the research result discussion the data on the sound waves of finite amplitude passing over a plane nozzle with transparent walls and a regulated angle of opening are used. The critical section dimension is 150×10 mm and the nozzle half-opening angle is 1 deg ($P = 4.8$ atm), and its construction is similar to that of the nozzle used in Ref. 6.

Results and Discussion

1) The propagation and reflections of sound waves in the settling chamber and in the nozzle, when the supersonic jet is internally excited, appear to be important, and without considering them one cannot obtain a plausible explanation of the changes produced in the jet and its acoustic near field under such excitation. The shadowgraph of the flow in the plane nozzle presented in Fig. 1a gives an idea of these processes. The test carried out has shown that the important role in forming the sound field in the nozzle is plaid by a configuration of the subsonic inlet part of Lavale nozzle. The wave propagation from HG (1) is followed by numerous waves reflected from the nozzle inlet part and from the internal surface of its divergent part (2–5). As it follows from the presented shadowgraph, the sound-wave propagation velocity in the nozzle and the angle under which the sound waves are incident upon the nozzle edge from inside vary within large limits. The sound intensity in the reflected waves is comparable with the sound intensity in the incident wave. It is known[7] that when the supersonic jet is under sound excitation the sound incidence angle on the nozzle edge is of importance in disturbance formation, and therefore the reflected waves can cause forming the disturbances not less in size and intensity than those formed by the plane wave. The consequence of such sound field structure in the nozzle is the radiation of numerous sound waves with different lenght scales in the acoustic near field of the supersonic jet (Fig. 1b). It seems that the use of sawtoothlike waves of finite amplitude corresponds better to the true processes in the combustion chambers, which are characterized by relatively high values of pressure fluctuations and by the presence of higher harmonics in the spectrum, than the sinusoidal waves usually used in theoretical considerations.[8]

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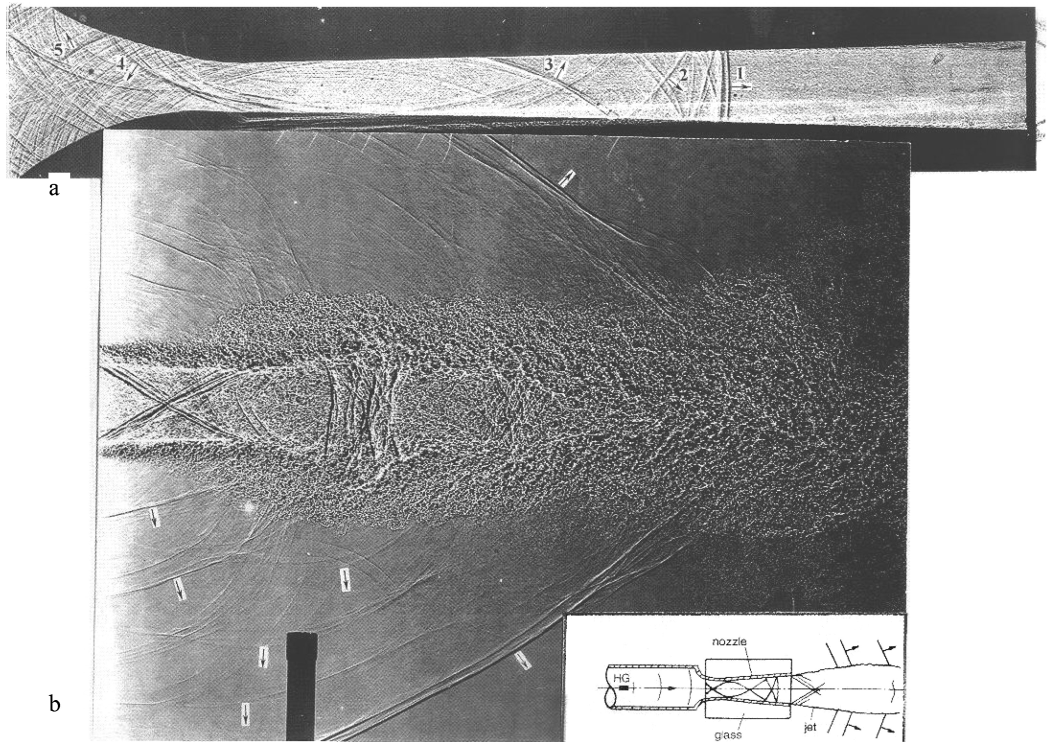

Fig. 1 Propagation of the sound wave of finite amplitude in the plane supersonic nozzle ($P = 4.8$ atm, $\alpha = 1$ deg): a) the sound waves in the nozzle; 1, plane wave and 2–5, reflected waves; and b) structure of the jet and sound waves radiated by the jet.

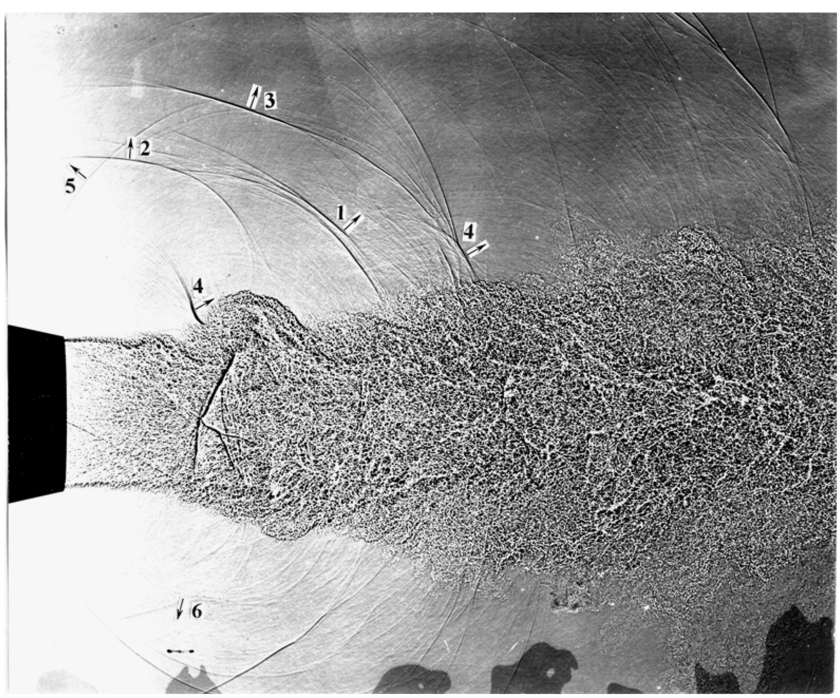

Fig. 2 Supersonic jet under internal longitudinal excitation by a sawtoothlike sound wave of finite amplitude ($P = 6.2$ atm, SPL = 165 dB): 1–3, sound waves issuing from the nozzle; 4, Mach wave; and 5 and 6, sound waves radiated by the jet.

2) In the case of axisymmetrical supersonic jet, the three-dimensional structure of the sound waves in the nozzle becomes more complex but, as one can expect, keeps its main properties observed at sound propagation in the plane nozzle. Figure 2 presents a typical shadowgraph of the axisymmetrical supersonic jet under internal longitudinal excitation by a sawtoothlike sound wave of finite amplitude. (All 21 shadowgraphs were made at different moments of time.) Along with the numerous sound waves issuing from nozzle (1–3), one can observe a typical Mach wave (4) formed by the disturbance appearing under sound excitation and moving along the jet boundary with supersonic velocity, as well as the sound waves (5 and 6), the sources of which are in the jet. Because, as was noted earlier, the sound waves reflected from the internal nozzle surface and incident upon the nozzle exit from inside possess the intensity commensurable with the sound intensity in the direct wave, the disturbances generated by them are also rather large. The length scale of the disturbances in the jet under sound excitation, which is assumed to be the distance between the nearest disturbances, is therefore not a constant value and depends on the value of the time interval at which the reflected sound waves arrive at the nozzle edge.

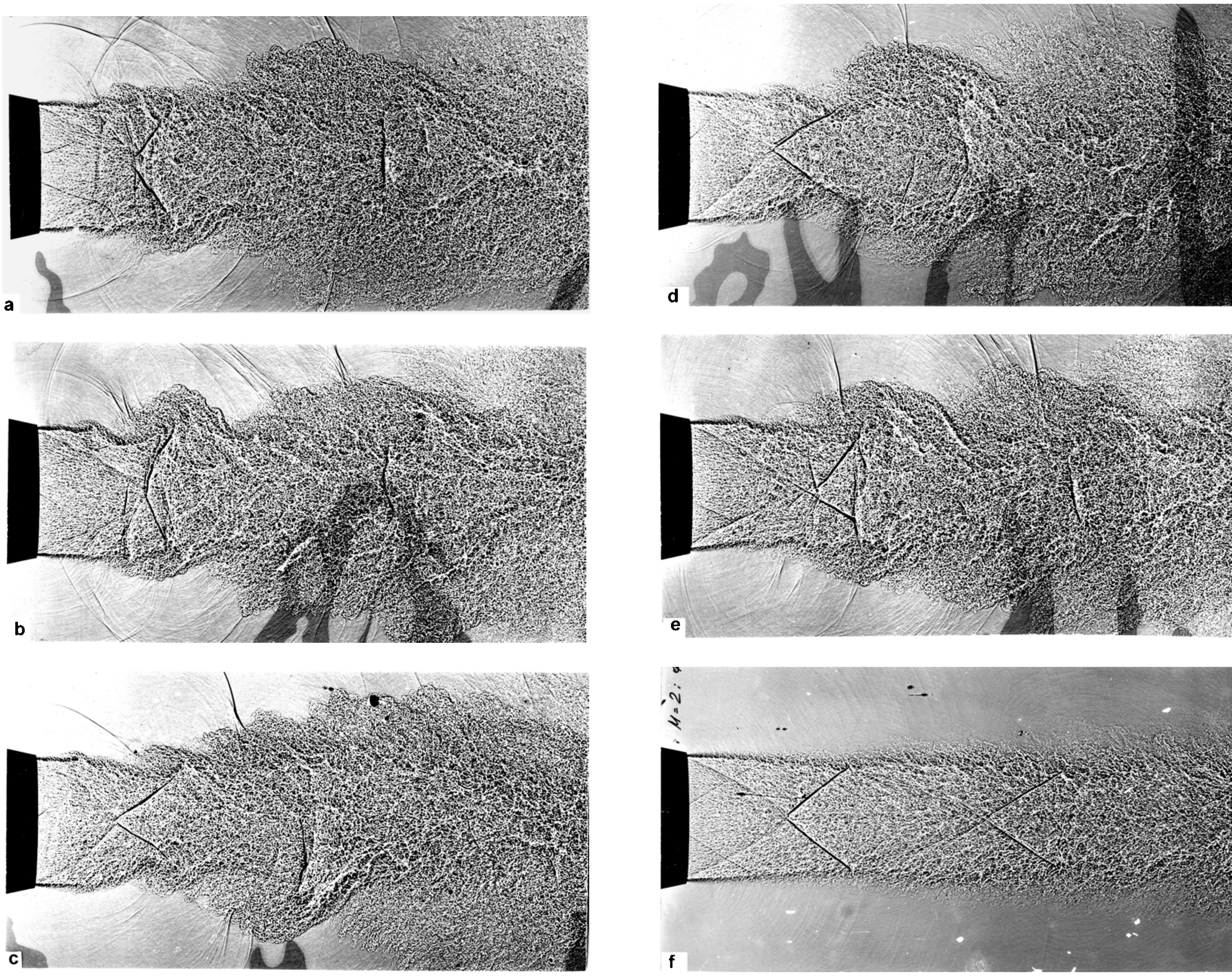

Fig. 3 Supersonic jet structure under internal longitudinal acoustic excitation: a–e) $P = 6.2$ atm, SPL = 165 dB; and f) an undisturbed jet.

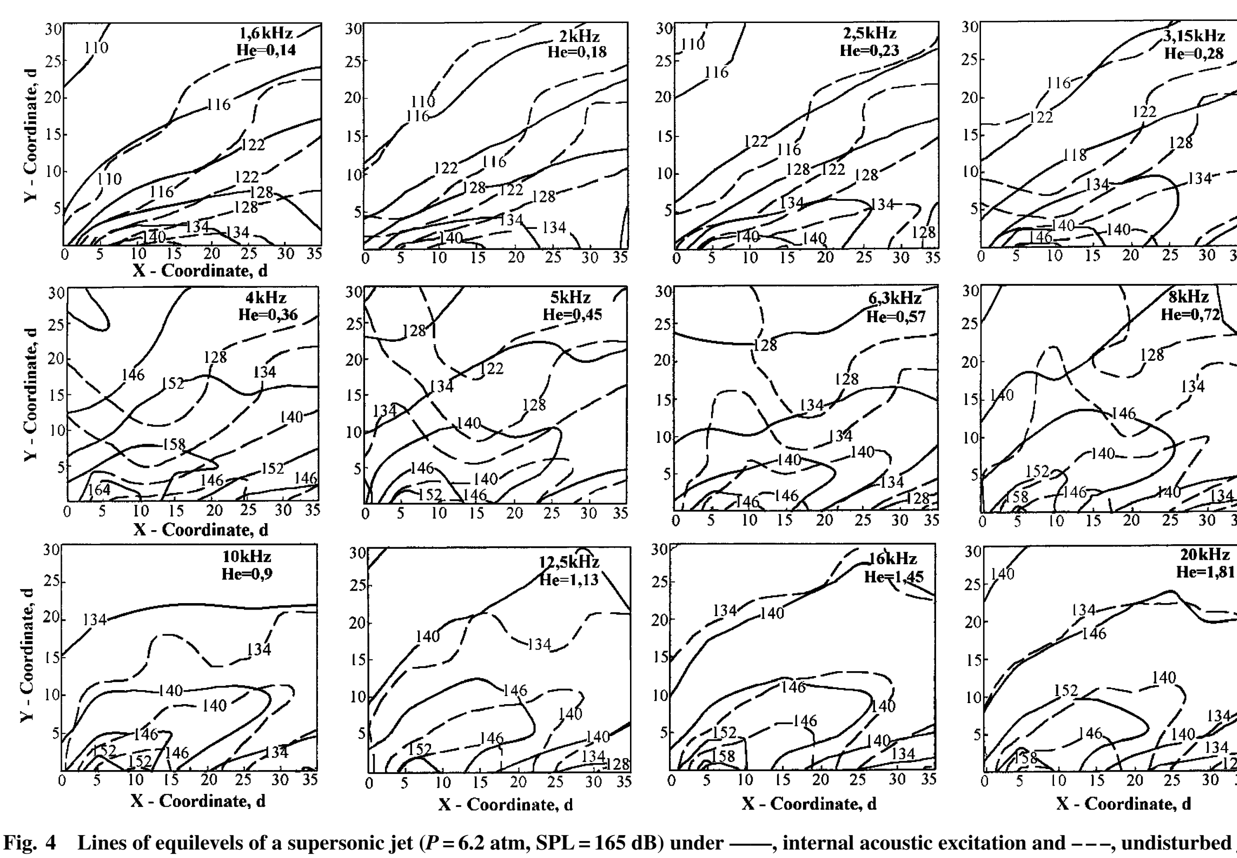

Fig. 4 Lines of equilevels of a supersonic jet ($P = 6.2$ atm, SPL = 165 dB) under ——, internal acoustic excitation and – – –, undisturbed jet.

These time intervals, in their turn, depend on the configuration of the inlet nozzle and the diameter of its critical section. Therefore the sound field of such a jet is deprived of exacting periodicity, as it is observed under external acoustic excitation. When the disturbance passes through the supersonic jet, the longitudinal dimensions of the first cell of the periodical jet structure and the proper jet shock-wave structure can substantially vary (Fig. 3). The shadowgraphs placed in this figure were made at random moments of time, but were presented in the sequence corresponding to the first cell longitudinal dimension increase.

3) The comparison between the equal SPL lines in $\frac{1}{3}$-octave frequency bands in the acoustic near field of the undisturbed supersonic jet and the jet under acoustic excitation shows (Fig. 4) that the spatial jet extent might decrease, but the level of noise in the near field increases. The SPL in the jet near field under acoustic excitation increases by 6 dB over the whole frequency range being studied, except the frequency band corresponding to the external excitation frequency. In the experiments carried out, the SPL in this frequency band increases by the value of ∼20 dB. The broadband noise sources in the supersonic jet under acoustic excitation shear in the nozzle exit direction. The noise sources at the frequencies corresponding to the peak of the radiated acoustic energy spectrum maximum are concentrated in the region at a distance of $\sim 5d$ from the nozzle exit in this case, and in the undisturbed jet the principal noise sources are concentrated in the region at a distance of $15d$ from the nozzle exit. The broadband noise level increase and the noise source shear upstream seem to be associated with radiation of the sound waves reflected from the internal nozzle surface, disruption of the proper shock-wave pattern, acceleration of the mixing process, and fast jet expansion.

Conclusions

1) Under internal longitudinal acoustic excitation of the supersonic jet, a system of sound-waves with different propagation directions associated with sound-wave reflection from the nozzle inlet part and from the walls of its divergent part is formed in the nozzle.

2) The investigated pressure fluctuation values in the settling chamber (SPL ∼ 165 dB) lead to a significant variation of the first cell dimension and of the whole shock-wave structure of the jet, when the disturbances caused by sound excitation pass through it.

3) The SPL in the jet near field under acoustic excitation increases by 6 dB over the whole frequency range investigated and in the frequency band corresponding to the external excitation frequency the sound pressure levels increase by the value of ∼20 dB. The broadband noise sources in the supersonic jet under acoustic excitation shear in the nozzle exit direction, and in the experiments carried out at the frequencies corresponding to the peak of the radiated acoustic energy spectrum maximum they are concentrated in the region at a distance of $5d$ from the nozzle exit.

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