Experimental study of sound field excited by a supersonic jet

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Results of experimental study of the acoustic waves generated by supersonic submerged air jet are presented. The sound pressure was measured within the frequency region between 20 Hz and 100 kHz by a set of 5 microphones mounted on the jet unit of T-326 wind tunnel at ITAM SB RAS. It is shown, that the level of generated acoustic modes is within 150–157 dB, the character of modes changes from harmonic to noise-like with the increase in the ratio of nozzle exit pressure to the atmospheric pressure. The source of the sound is on the jet axis near to the area of transition to the jet subsonic velocity.

Introduction

The advancement of experimental aero- and gas dynamics calls for the improvement both of systems of control for average parameters of supersonic flows and real-time measurements of the level and spectral composition of pulsation characteristics. Sensors, used at present, contribute distortions in the flow structure and often have a low speed of response. The methods, based on the flow transmission by a laser beam, are more convenient for measuring the pulsations in flows. Based on relations of the turbulence theory of incompressible liquid, the optical methods are widely used to measure parameters of the atmospheric turbulence[1,2] and subsonic turbulent flows.[3,4] In case of supersonic flows, it is necessary to take into account not only the temperature fluctuations but also the pressure fluctuations, and, as opposed to the atmospheric turbulence, strong inhomogeneity of the flow parameters.

In recent years, the theoretical papers have appeared (see, for example, Ref. 5), where the attempts were made to construct an electrooptical model of parameter fluctuations of compressible gas flows. However, the results obtained can be considered only as initial stage of the study of light propagation in supersonic flows.

The results of experimental investigations of the laser radiation transmission through supersonic air jet are given in Refs. 6 and 7. It follows from these works that under definite conditions the sound waves, generated by supersonic flows, can have a pronounced effect on the sensing radiation.[8,9] Actually, in experiments,[6] where a large part of the sounding beam propagation path was located beyond the jet, time spectra of sounding beam intensity fluctuations with two maxima were observed. A high-frequency maximum in the range 30–60 kHz was determined by fluctuations of the refractive index of air density directly in the jet itself; the second, low-frequency maximum was in the range 1–1.2 kHz.

The reason for the occurrence of low-frequency intensity fluctuations of sensing radiation[6] is the scattering by sound waves generated by a supersonic jet. This is confirmed by the subsequent experiments,[7] where the optical path length beyond a jet was much less. In the experimental spectra of intensity fluctuations of the sensing laser radiation the low-frequency maximum was lacking.

The investigation of sound waves, generated by the compressible gas flow, is of great importance.[8,9] On the one hand, this is necessary for studying a possibility of decreasing the noise level of jet vehicles, on the other hand, this is important for diagnostics of the flows themselves, since the noise level depends on the flow characteristics. The results of analysis of sound fluctuations, occurring at the outflow of the supersonic air jet, are presented in this paper.

Experiment and processing procedure

The base for experiments was the T-326 supersonic aerodynamic tunnel of the Institute of Theoretical and Applied Mechanics of SB RAS. A supersonic jet was formed by a convergent Laval nozzle with a diameter of 30 mm at the nozzle pressure ratios npr, equal to 5 and 9. The Mach jet numbers, determined by isoentropic gas broadening, for the above values of npr were equal to 1.71 and 2.09.

Measurements of sound were made in the frequency range between 20 Hz and 100 kHz with the use of a line of 5 microphones of 6 mm in diameter. The measurements were conducted at three different configurations of the arrangement of microphones relative to the jet (Fig. 1): in parallel to the jet at the distance $r = 135$ mm below its axis with the step $\Delta x = 20$ mm at distances $x = 25 \div 250$ mm from the nozzle (*a*); around a circle of a radius of 140 mm (spaced by 45°) normally to the jet at a

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distance x = 135 mm from the nozzle (b); horizontally across the jet 135 mm below its axis at distances of 25 and 135 mm from the nozzle (c).

Based on the measurement results, spectral densities and cross-correlation functions of the sound wave between the microphone M0 and all other microphones were calculated. For configuration 1, the microphone M0 was located at a distance of 250 mm from the nozzle and remained there when moving other four microphones.

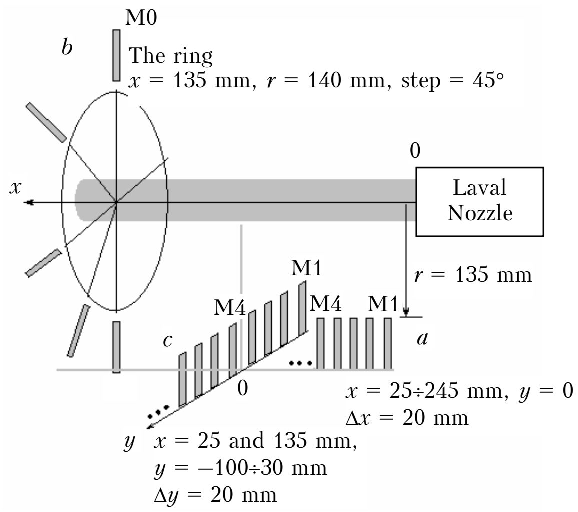

Fig. 1. Configurations of microphones in the Eifel chamber.

Results of measurements

1. Spectra and correlation functions of a sound wave

The measurements have shown that at npr = 5 the sound, generated by the jet, has one clearly defined harmonic component at the frequency $f = f_m \approx 3.03$ kHz. Figure 2 presents examples of acoustic wave fluctuation spectra, calculated with the use of the fast Fourier transform.

The second maximum at $f \approx 2f_m$ with the amplitude by 5–10 times less is also observed in the spectrum. The dependence of the maximum frequency on the Stenton number $\mathrm{St} = fd/V_c$ (V_c = 341 m/s is the sound velocity at $t \approx 16$°C, d is the nozzle diameter) is close to the literature data.[8] At npr = 9 the main clearly defined harmonic is lacking, the sound generation occurs in a series of spectral intervals.

Table shows the frequency and the wavelength λ of the main harmonic at npr = 5 and the frequency of harmonic component with the maximal amplitude at npr = 9. It is evident that the wavelength at npr = 5 is roughly equal to 110 mm, and at npr = 9 – to 142 mm. For comparison, the wavelength, which was estimated in Ref. 6 by data of measuring the intensity fluctuations of a sensing laser beam, was between 110.7 and 132.8 mm when using the ratio of maximal frequency of the spectral function f_{m1} with the typical scale of inhomogeneity for the atmospheric turbulence $\lambda = l = 0.4V_c/f_{m1}$ (f_{m1} = 1000–1200 Hz).[6]

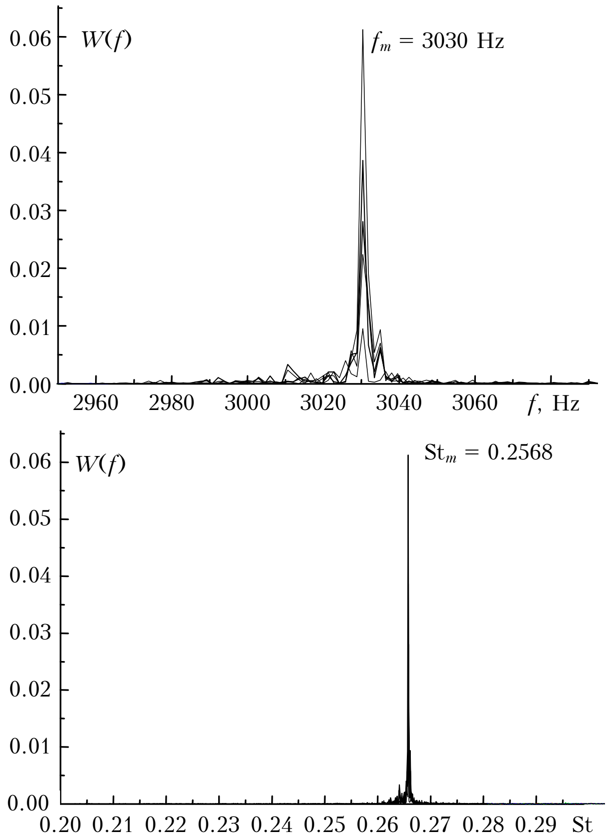

Fig. 2. Spectra of acoustic wave fluctuations at npr = 5.

Table. Frequency and wavelength of generated sound waves

Configuration of experiment	npr = 5		npr = 9	
	f_m, Hz	λ, mm	f_m, Hz	λ, mm
In parallel to the axis	3004–3021	110–109.5	2333–2350	141.9–140.9
The ring	3030–3033	109.2	2348–2355	141.0–140.6
Perpendicular to the axis:				
x = 25 mm	2995–3007	110.5–110.1	2329–2341	142.2–141.4
x = 135 mm	2994–998	110.6–110.4	2329–2332	142.2–141.9

To determine the sound wave shape, the cross-correlation of acoustic signals, measured by microphones M0...M4, was calculated. Figure 3 shows the coefficients of time correlation of acoustic signals between microphones in the measurement configuration of Fig. 1a.

Figure 3 shows that the coefficients of cross-correlation vary by the harmonic law within 0.15–0.40 and preserve their amplitude in time, that corresponds to the presence of a clearly defined basic harmonic in the spectrum. At npr = 9 the correlation decreases rapidly with time, that corresponds to the noise character of the spectrum in this case.

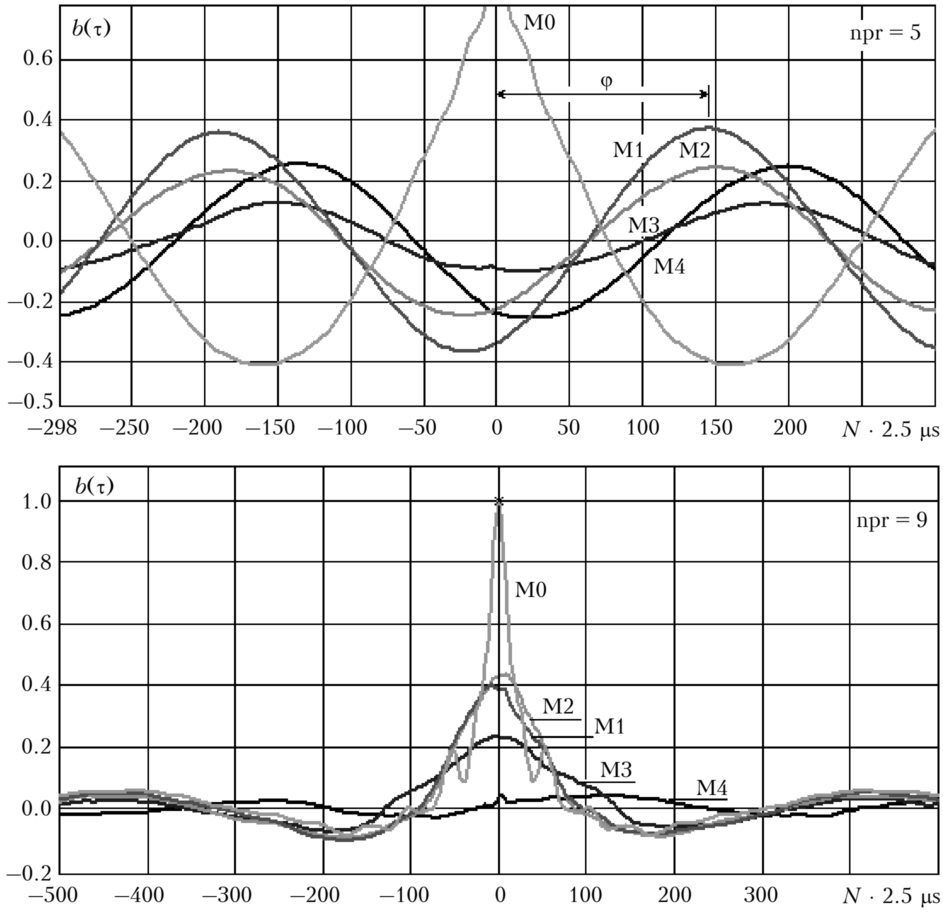

Fig. 3. Coefficients of time correlation of acoustic wave. M0 is the coefficient of autocorrelation of the first microphone, M1... M4 are the coefficients of cross-correlation between the microphone M0 and microphones M1, M2, M3, M4; φ is the phase shift.

2. Shift of the acoustic wave phase

The acoustic wave phase shift was determined by the position of maxima of correlation functions M0, M1, M2, M3, M4 at the time scale as is shown in Fig. 3. The results of the phase shift determination at different measurement configurations are given in Fig. 4.

For configuration from Fig. 1*a* (Fig. 4*a*), the phase shifts were determined with respect to the microphone, located at a 250 mm distance from the nozzle. The presented data show that the phase shift grows linearly with approaching the nozzle and has a minimum at a 225 mm distance. To interpret the experimental data, the phase shift φ between the microphones was calculated under the assumption that the generated acoustic wave was spherical, from the distance differences ΔL between the microphone at x_0 = 225 mm and all others (see Fig. 4*d*) with the use of relation

$$\varphi(x) = \pi\Delta L/\lambda,$$

where

$$\Delta L = [(x - x_0)^2 + h^2]^{1/2} - h.$$

Figure 4*a* shows that the calculated data are close to the experimental dependence. This allows a conclusions that the sound source is located at a distance of 225 mm from the nozzle; and at a distance of 135 mm from the jet axis the acoustic wave is close to the spherical one. The phase shift between microphones, located at distances of 225 mm and 25 mm from the nozzle, is about 2.75 π or 1.4 λ.

The measurements in the second configuration from Fig. 1*b* (Fig. 4*b*) show that the phase shifts between the microphone M0 and the others are close to each other and fall in range 0.7–0.9π. The conclusion about the closeness of phase shifts between microphones is valid also for configuration from Fig. 1*c* (Fig. 4*c*) when measuring at the distance x = 135 mm from the nozzle. In this case the phase shifts fall in range 0.95–1.05 π. This points to in-phase oscillations in the plane transverse to the jet, in other words, to the presence of zero (varicose) oscillation mode.[8,9]

Figure 5 shows the results of numerical simulation of the sound field generated by a supersonic jet.[8] It is seen that the sound wave source

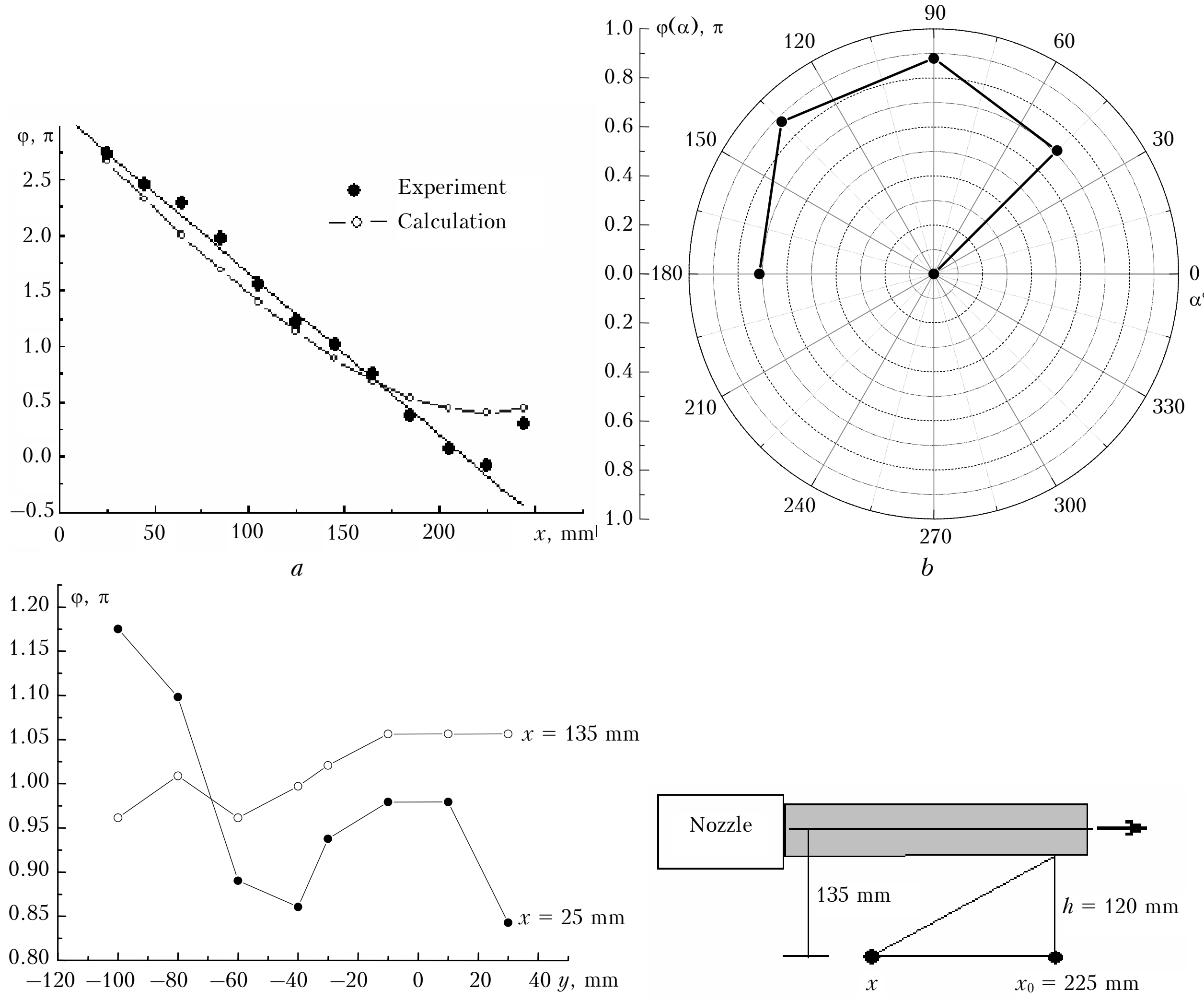

Fig. 4. The phase shift of acoustic waves in measurements by configurations of Fig. 1*a* (*a*); Fig. 1*b* (*b*); Fig. 1*c* (*c*) and the illustration to the calculation of phase shift (*d*).

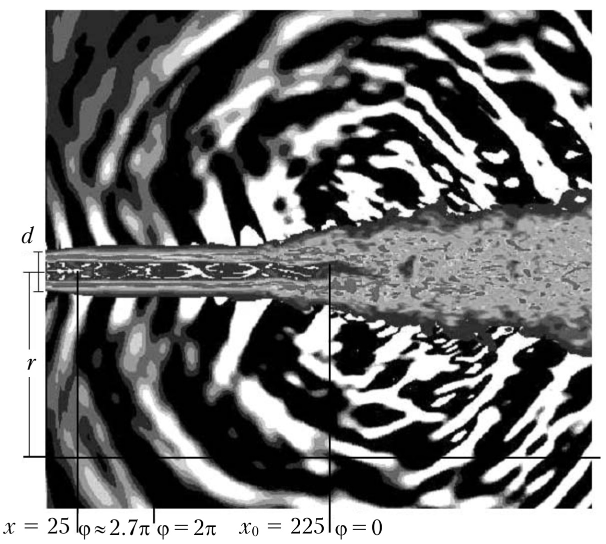

Fig. 5. The results of numerical simulation of acoustic field[8] as compared with data on the phase shift in the configuration of Fig. 1*a*.

is located close to the transition from the supersonic jet flow to the subsonic one. At a certain distance from the source the wave becomes close to a spherical one. In this case, the phase shift in the wave front above and under the jet is observed. All these facts are in the qualitative agreement with experimental data in Fig. 4.

For the comparison in more detail, figure 5 shows an approximate (relative to the calculation) disposition of microphones along the jet during measurements by configuration from Fig. 1*a* and estimation of the phase of the simulated acoustic field at different distances along the jet. It is evident that the acoustic wave phase at the jet beginning $\varphi = 2.7\pi$ is close to the experimental value $\varphi = 2.75\pi$ at a distance of 25 mm from the nozzle. The location of microphones was determined relative to the nozzle diameter d (Fig. 5) in such a way that h/d and x/d were equal to the experimental data $h/d = 135/30$ and $x/d = 25/30$.

3. The sound pressure level

In the measurements, the microphone calibration was made, which enabled the estimation of the sound pressure level, generated by the supersonic jet, using the calculation of the root mean square deviation of acoustic signal fluctuations. The results of the processing are given in Fig. 6 for all above experimental configurations.

It is following from obtained data that the sound pressure level at the distance of 135 mm from jet axis is within 151–156.5 dB for all measurement configurations at npr = 5. Near the nozzle at the distance of 25 mm it can be seen strong inhomogeneity of sound pressure on jet cross section. At npr = 9, sound pressure is by 1.5–2 dB less than at npr = 5. At the same time, the character of pressure changing along and across jet is the same as at npr = 5 for all measurements configurations.

Conclusions

The measurements of acoustic oscillations, generated by a supersonic air jet of the T-326 wind tunnel jet unit at ITAM SB RAS, allow the following conclusions.

1. The level of acoustic pressure close to the jet at the ratio between the output pressure from the nozzle and the atmospheric pressure, npr = 5, is within 151–156.5 dB. The increase of the output pressure up to npr = 9 leads to a slight decrease of the level of the generated sound.

2. At npr = 5 the generated acoustic oscillations are close to the harmonic ones at a frequency of 3 kHz. The increase of output pressure up to npr = 9 results in the qualitative change in the generated acoustic signal, its spectrum extends, the generation is realized in several frequency ranges, the sound generation mode becomes multimode.

3. The sound source is located in the transition zone from supersonic velocities of the jet flow to subsonic ones. For the jet unit of the T-326 wind tunnel it is located on the jet axis at a 225 mm distance from the nozzle. At a certain distance from the source the generated sound wave becomes close to the spherical one.

4. The experimental results do not contradict to the known results of numerical simulation of sound fields, generated by supersonic flows.[8]

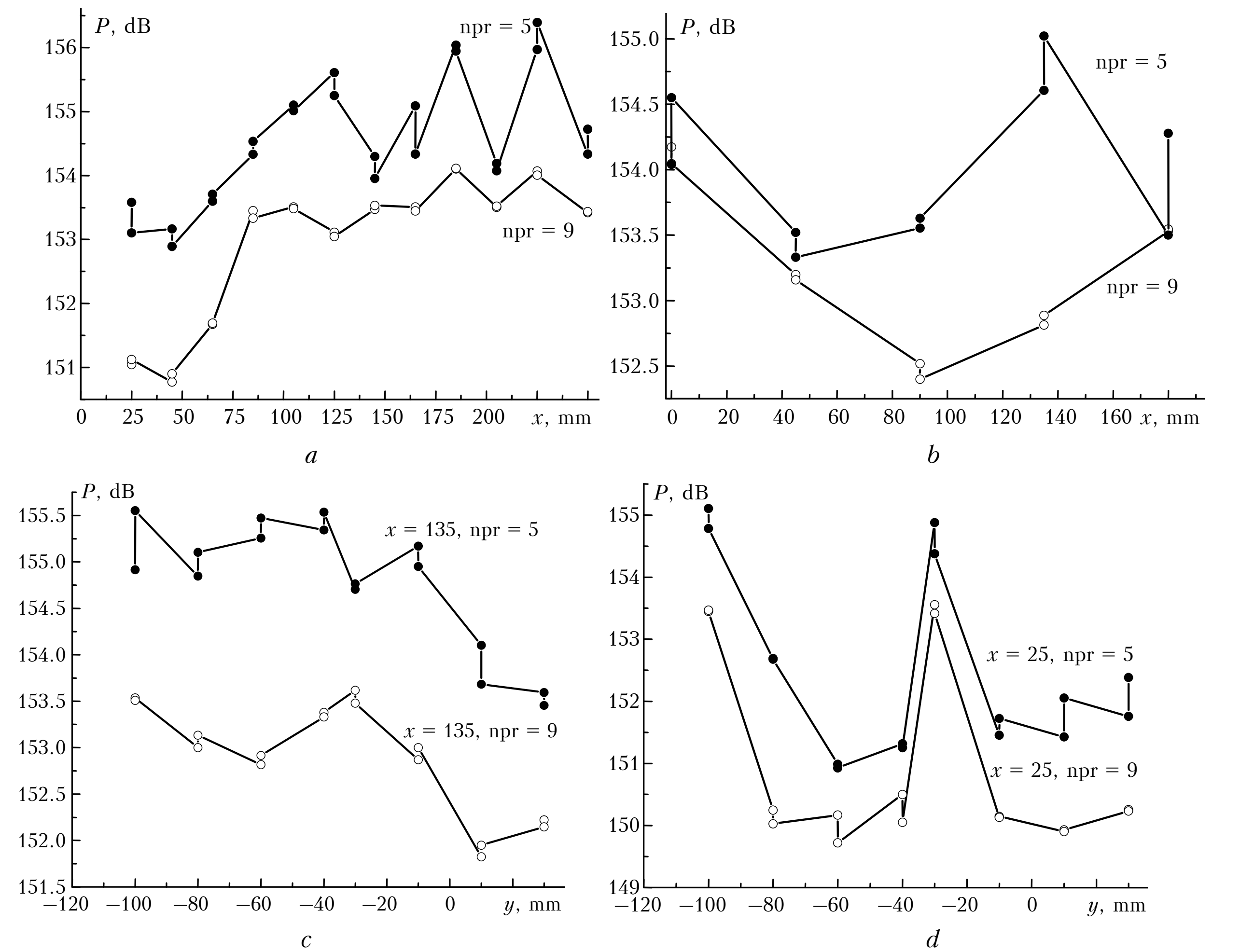

Fig. 6. The level of acoustic oscillations at npr = 5 and 9 with configurations: along the axis (*a*), in a circle (*b*), in the transversal section at *x* = 135 mm (*c*) and *x* = 25 mm (*d*).

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