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VELOCITY FIELD STRUCTURE OF THE INTENSE SOUND WAVE NEAR A WAVEGUIDE OPEN END

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Nonlinear phenomena arise when an intense sound wave passes through a waveguide open end. Spatial structure of the velocity field is investigated by means of the hot-wire anemometer. Anemometer registers both oscillations and an acoustic flow. A method is suggested to split and to estimate these parts of the velocity. If the acoustic flow velocity exceeds the oscillation velocity amplitude then the flow velocity is evaluated as the change of the root mean square value of the hot-wire anemometer's signal. In this case, the oscillating velocity amplitude is computed by the signal dispersion. In the absence of the flow, the change of the root mean square value of the hot-wire anemometer's signal defines the effective value of the oscillating velocity. The estimation of the velocity magnitude is performed using calibrated dependence of anemometer voltage vs. flow velocity. In the proximity of the waveguide open end, the radial and axial velocity components of both parts of the velocity field is registered. Characteristic regions are observed inside as well as outside of the waveguide open end.

The nonlinear phenomena arise when the intense sound wave passes trough the screen with orifices. This leads to the concept of the nonlinear screen impedance. The same nonlinear impedance has an open end of the tube.

The aim of this paper is to develop a method of a quantitative estimation of oscillating and hydrodynamic velocities and to investigate the spatial structure of the nonlinear phenomena near the waveguide open end.

The intense sound wave was driven by the low frequency loudspeaker. The sound pressure level (SPL) of the wave was range up to 160 dB. The cone concentrator matches a loudspeaker diffuser of 36.6 cm diameter to a brass tube of 2.35 cm internal diameter and 74 cm length. Velocity measurements were made by means of the constant temperature hot-wire anemometer (HWA) "DISA". HWA probe is a tungsten wire of 2 mm length and 10 μm diameter. The wire is heated to the temperature of 200 °C. Resonant frequencies of the experimental setup are equal to 175 Hz, 268 Hz and 358 Hz. They were founded by the maximum value of the HWA signal when the probe was placed on the waveguide axis in the outlet cross-section. Frequencies 175 Hz and 358 Hz are linear resonant frequencies. Meanwhile, the frequency 268 Hz may be considered as the frequency of the second nonlinear resonance.

HWA probe registers a total velocity of media movement which includes oscillations, a mean flow and turbulent pulsation. As the result, the signal looks like a chaotic process. For the determination of the prevailing process the signal spectrum is had to analyze. The harmonic sound wave is reflected in spectra as a doubled frequency line because the HWA detects the measuring signal. The fundamental frequency is presented in spectra when the acoustic flow arises. The turbulence is reflected as a broadband noise in spectra.

The measured signal is recorded by the 80486 computer. The 16 seconds record is performed by means of the analog-to-digital computer board LA-2 of JSC "Rudnev-Shilyaev". Final power spectra are the mean of 16 spectra from 1 second part of the original record. Spectra are computed using the Hanning window function. The data processing packet MATLAB 5.1 was used for calculations.

If the fundamental frequency prevails in spectra, it means that the acoustic flow velocity exceeds the oscillation velocity amplitude of the sound wave. In this case, the next estimation method is proposed to evaluate the oscillating v_{osc} and hydrodynamic v_{hd} velocity component.

The acoustic flow velocity is found as the change of root mean square values of the HWA signal $\left(u-u_0\right)$, where u_0 - HWA reading in the absence of the sound field, u - in the presence of the sound field:

$$v_{hd} \propto \left(u-u_0\right). \tag{1}$$

Accordingly the oscillating velocity amplitude can be defined by means of the dispersion Du of HWA signal:

$$v_{osc} \propto \sqrt{Du}\ . \tag{2}$$

For the quantitative estimation of the velocity the calibration dependence of HWA probe in the constant flow is used. Denote the constant flow velocity by v_{flow}. The next dependence was found at measurements in the aerodynamic tube:

$$v_{flow} = 3.83 \cdot \left(u-u_0\right)^{2.33} \text{ [m/s]}. \tag{3}$$

The acoustic flow velocity value is computed by means of the calibration dependence (3), i.e. $v_{hd} = v_{flow}$.

The oscillating velocity amplitude is defined from the relation between v_{hd} and v_{osc} (see equations (1) and (2)):

$$v_{osc} = \frac{\sqrt{Du}}{u-u_0} \cdot v_{hd}\ . \tag{4}$$

When the flow velocity and the oscillating velocity amplitude have closely spaced values the quantitative estimation presents difficulties and can be made by the analysis of the signal oscillogram only.

If the intense sound wave propagates in the absence of a flow or when the flow velocity is very small the doubled frequency line prevails in spectra. In this case, a value of the oscillating velocity amplitude is defined as the change of the root mean square value of HWA signal. Then the oscillating velocity amplitude is evaluated with the help of the calibration dependence (3), i.e. $v_{osc} = v_{flow}$.

In distinction to the case of a shock wave when both the wave process inside the tube and the boundary condition have nonlinear character [1]. In the case considered we deal with a linear process of the intense sound wave propagation in a tube and take into account just the nonlinear outlet boundary condition. It is believed that the modified two microphone technique [2] may be used to measure the field properties in the tube and the open end impedance. The absence of a marked harmonic distortion in the microphone signal spectra serves as a guide for this. Besides, velocity values computed by the two microphone technique and that estimated by HWA measurements coincide with 15 % precision.

Measurement results of the active component of the open end impedance R_1 vs. velocity v in the waveguide outlet cross-section are shown on the fig. 1. The tests were made when SPL was alternated from 130 dB to 160 dB. As the plot shows the resistance value is small and there is a trend to an increase of its value. It takes place when the velocity in the waveguide outlet cross-section reaches approximately 5 m/s (SPL about 155 dB). Thereafter the resistance keeps its value and even goes down as the velocity is increased. Such amplitude dependence differs from the corresponding resistance dependence of the orifice in the screen as the orifice resistance is proportional to the velocity in the orifice. Reactive component of the impedance makes up 1 % of rc and it coincides with the linear behavior calculation. As the result more than 80 % of the sound energy is reflected from the open end and the intense standing wave takes place inside the waveguide. The radiated sound energy involves less than 10 %.

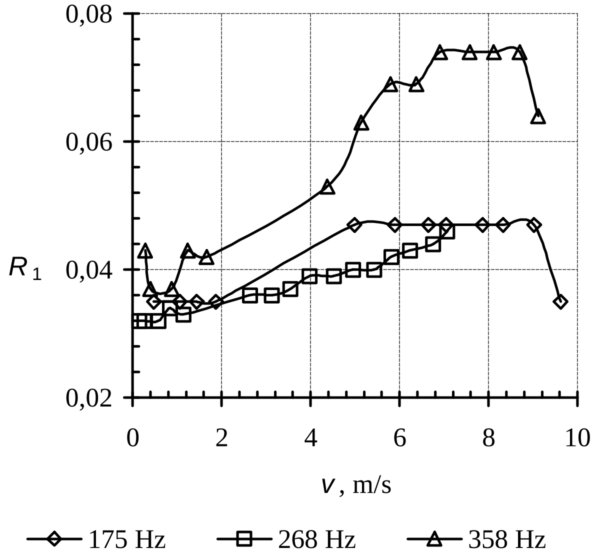

Fig. 1. Dimensionless resistance R_1 vs. velocity v in the waveguide outlet cross-section.

To investigate the spatial picture of the velocity field in the proximity of the tube open end, the two probe orientations were used. The axial velocity component along the waveguide axis and radial velocity component were measured. As the HWA probe coordinate device the lathe support was used. The support supplies the displacement with a precision of 0.01 mm.

By applying the proposed method of the quantitative velocity assessment, the distribution of the axial velocity component along the waveguide axis was determined both outside and inside the tube. Based on the signal spectra analysis we had discovered that only sound oscillations exist inside the tube while the acoustic flow prevails outside. Oscillations were registered outside the tube only at the distance 1.5 cm. Their maximum takes place at the distance 1.5 cm inside the tube. Experimental data is presented on fig. 2a. Positive values of the axial coordinate are directed from tube open end to the outer space and negative - inside the waveguide. The acoustic flow exists at long distances from the outlet. The flow velocity reaches 9 m/s. The maximum of the oscillating velocity amplitude is equal to 11 m/s.

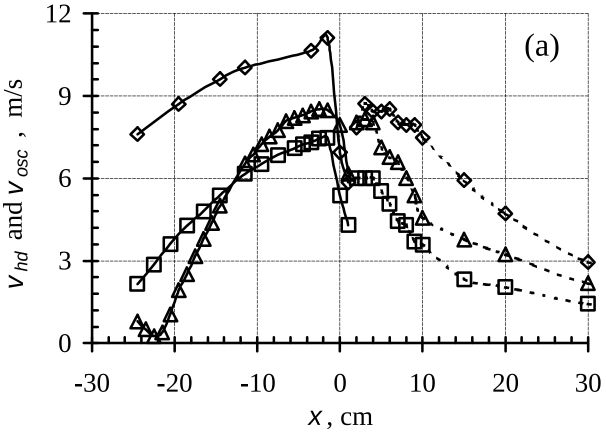

Fig. 2a. Distribution of the acoustic flow velocity outside the tube (dashed lines) and the oscillating velocity amplitude inside the tube (solid lines) on the waveguide axis at frequencies: 175 Hz - ◊, 268 Hz - ,
358 Hz - Δ.

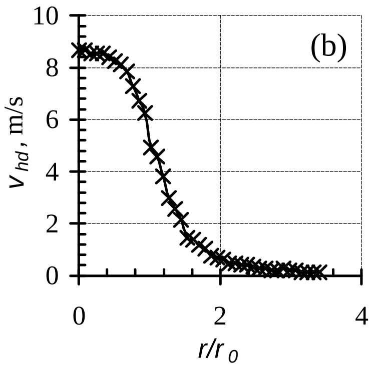

Fig. 2b. The mean velocity profile of the acoustic flow (175 Hz, 160 dB).

Fig. 2b shows the profile of the axial component of the acoustic flow velocity in the cross-sections that are placed at the distances from 2 to 6 cm away from the waveguide open end. The radial coordinate is expressed in terms of the waveguide radius r_0.

As illustration of the above mentioned phenomena the vector plot of the velocity field is shown on fig. 3. The near field represents a complicated picture. An acoustic flow is observed beginning from the distance of 2 cm away from the waveguide open end.

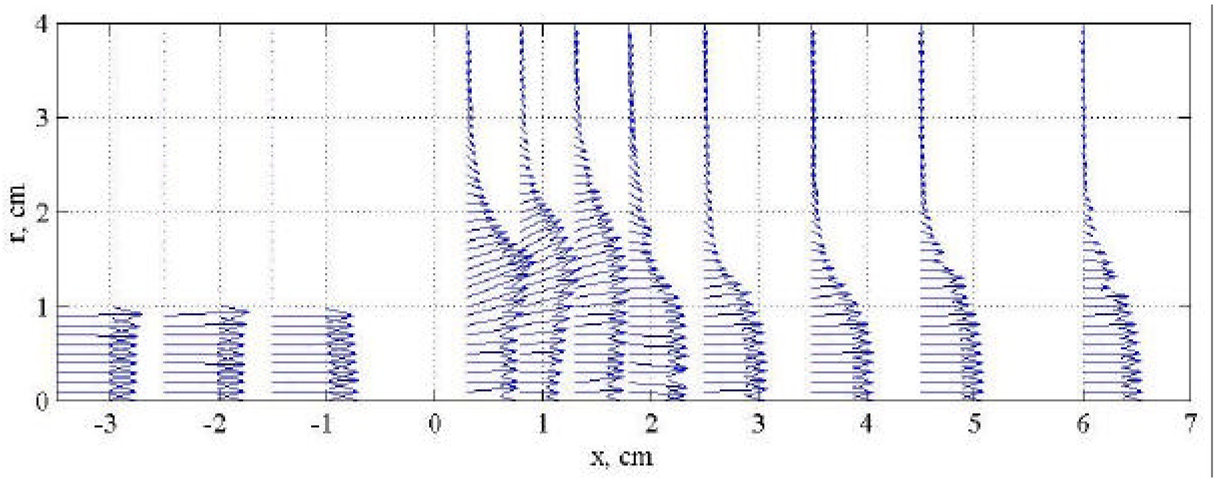

Fig. 3. Velocity field structure in the proximity of the waveguide open end (SPL 160 dB, frequency 175 Hz, $x < 0$ is inside the waveguide).

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