Estimation of the influence of acoustic radiation direction on the acoustic wave interference along short surface paths

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The influence of directivity of an acoustic radiation source on the interference of the direct wave and the wave reflected from the surface during the sound propagation along short surface paths is discussed. Theoretical and experimental data are compared.

When studying the processes of acoustic wave propagation along surface paths, it is necessary to take into account numerous factors influencing the amplitude and phase characteristics of signals. One of such factors is the interference, at which the direct wave and the wave reflected from the surface are summed at the point of detection. Both theoretical and experimental papers on the sound interference in the atmosphere are mostly devoted to statistical characteristics of signals. In this case, the interpretation of obtained results is usually based on the assumption that emitted acoustic waves are either spherical or plane.

In this paper, the emphasis is on the effect, which arises when dealing with a nonisotropic directional pattern of the acoustic radiation source. The consideration of this effect allows errors in interpretation of experimental results to be avoided. This effect can be demonstrated by mere variation of only the carrier frequency of acoustic signals at a fixed geometry of the experiment. Below we briefly describe the technique used and the results of the experiments carried out at a short path over a rigid surface (plane roof of a building) under the conditions of a gentle breeze.

To check theoretical models and to study the influence of atmospheric conditions on the interference of acoustic waves, we constructed an acoustic bench including a controlling computer generating signals through a standard sound board and receiving signals through a specialized multichannel ADC, a power amplifier of transmitted signals, a horn source of acoustic radiation, receiving microphones installed at different levels in the vertical plane and connected to the corresponding multichannel amplifier of the received signals, from which signals came to the ADC. Current atmospheric conditions were monitored at an ultrasonic meteorological station located near the sound propagation path at a height of about 1.6 m. The bench operation consisted in the consecutive transmission of a set of frequencies with an automated transition from one frequency to another. The schematic of the experiment is shown in Fig. 1.

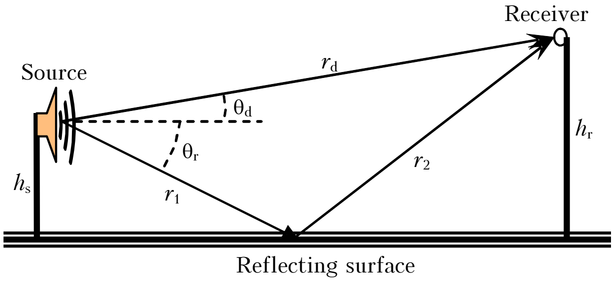

Fig. 1. Schematic of the experiment.

Assuming the fulfillment of the conditions, permitting the application of the ray theory of acoustics to a static and nonstratified medium, we can write the equation for the square amplitude of the pressure $p(f)$ of an acoustic wave taking into account the directivity of only the acoustic radiation source in the form

$$p^2(f) = A^2(f)B^2(f)D(f,r_1,r_2,r_d,\theta_d,\theta_r), \qquad (1)$$

$$D(f,r_1,r_2,r_d,\theta_d,\theta_r) = r_d^{-2}\, e^{-2r_d\alpha(f)}\{g^2(\theta_d,f) + |Q|^2 g^2(\theta_r,f) + 2|Q|\,C(f)\,g(\theta_d,f)\,g(\theta_r,f) \times \cos[k(r_1 + r_2 - r_d) + \Omega]\}. \qquad (2)$$

Here $A(f)$ is the amplitude-frequency characteristic (AFC) of the source; $B(f)$ is the AFC of the receiver; $g(\theta, f)$ is the normalized amplitude directional pattern (DP) of the source; θ_d and θ_r are the angles between the DP axis of the source and the direction to the receiving microphone and to the point of reflection from the surface (see Fig. 1); r_d is the distance between the source and the receiving microphone; r_1 and r_2 are the distances from the source to the point of reflection and from the point of reflection to the receiver; $C(f)$ is the coherence function of the direct and reflected signals; $|Q|$ is the absolute value of the sound reflection coefficient from the surface; Ω is the phase shift in the reflected acoustic wave (complex sound reflection coefficient from the surface

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$Q = |Q|\,e^{i\Omega}$); $\alpha(f)$ is the amplitude sound absorption coefficient calculated by the ANSI (USA) standard taking into account the current values of the temperature, humidity, and air pressure; $k = 2\pi f/c$ is the wave number; f is the frequency; c is the acoustic speed. In equalities (1) and (2), it is assumed that the sound absorption at the direct and reflection paths is roughly the same, and the approximation $r_1 + r_2 \approx r_\mathrm{d}$ is accepted in amplitude factors.

Since spontaneous changes in the AFC of the acoustic source are possible during the operation (and they were observed in our measurements), the transmitted signal should be continuously under control. For this purpose, during the experiments, we placed a controlling receiver (microphone) near the source. The influence of reflections from the surface on the amplitude of the controlling receiver signals was neglected (this is partly justified due to nonsphericity of DP of the source used in the experiment).

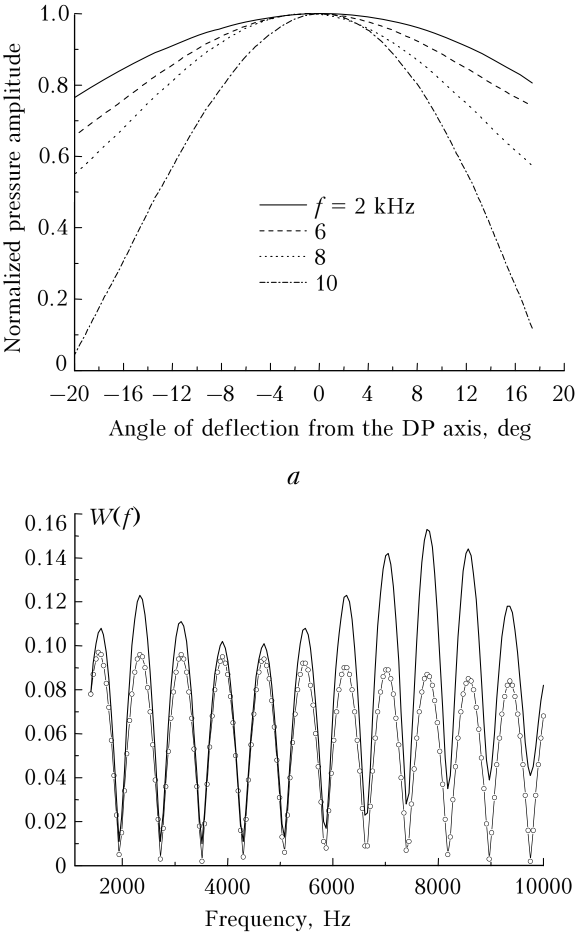
The combination of signals of the main and controlling acoustic receivers (microphones) allows Equation (1) to be transformed to the form convenient for comparison of experimental and theoretical results, and thus we can avoid the necessity of estimating the source AFC:

$$W^2(f) = p^2(f)/p_\mathrm{c}^2(f) =$$
$$= \kappa^2(f)\,g^{-2}(\theta_\mathrm{c},f)\,r_\mathrm{c}^2\,D(f,r_1,r_2,r_\mathrm{d},\theta_\mathrm{d},\theta_\mathrm{r}). \qquad (3)$$

Here $p_\mathrm{c}(f)$ is the acoustic pressure amplitude at the controlling microphone; r_c is the distance between the source and the controlling microphone; θ_c is the angle between the source DP axis and the direction to the controlling microphone. The function $\kappa(f) = p^0(f)/p_\mathrm{c}^0(f)$ takes into account AFC of the receivers and is estimated at the preparatory stage. Here $p^0(f)$ and $p_\mathrm{c}^0(f)$ are the amplitudes of acoustic pressure measured respectively by the working and controlling microphones at the source DP axis at an equal small distance from the source. The source DP $g(\theta,f)$ is also measured at the preparatory stage. The approximation of experimental κ and g values by some functions allows us to use their analytical representation in Eq. (3).

After the pervious calibration measurements, having fixed spatial positions of the source and the receivers, we can calculate the right-hand side of Eq. (3), which depends only on the frequency provided that the experiments are conducted under the calm conditions. The coherence function $C(f)$ is constant and equal to unity (the absence of turbulence in the wind and temperature fields), the sound absorption is constant (no significant changes in temperature, humidity, and pressure of air). The left-hand side of Eq. (3) is estimated from experimental results. Thus, in the correctly conducted experiments, it is possible to check quite efficiently the theoretical models forming the function $D(f, r_1, r_2, r_\mathrm{d}, \theta_\mathrm{d}, \theta_\mathrm{r})$.

Since in our experiments the distances between the sound source and receiver, as well as their heights are small, it is possible to restrict the approximation of the measured DP of the transmitter by an analytical equation to only its main lobe. The results of approximation of the source DP used in our experiments by the Gaussian function for several frequencies are shown in Fig. 2*a*.



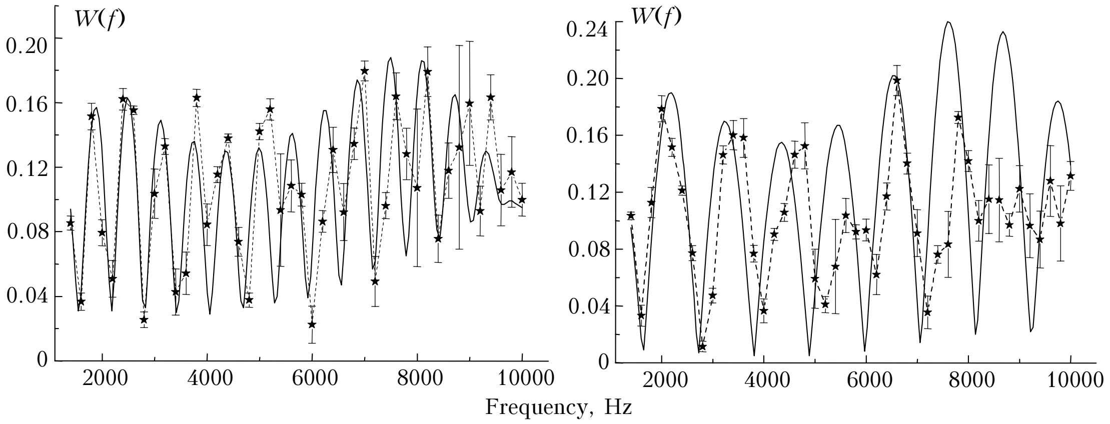
a

b

Fig. 2. Approximation of the normalized directional pattern of the real acoustic source for several frequencies (*a*) and amplitude of the signal calculated by Eq. (3) for the spherical (curve with symbols) and nonspherical (solid curve) sources (*b*).

Figure 2*b* demonstrates the influence of nonsphericity of the acoustic source DP on the regime of interference of the direct wave and the wave reflected from the surface. This figure shows $W(f)$ calculated for the case that the source has isotropic DP (curve with symbols) and the case of DP shown in Fig. 2*a*. It was assumed in the calculations that the heights of the acoustic source and receiver, as well as of the calibration microphone, are identical and equal to 1.5 m, the distance between the acoustic source and the working microphone r_d = 10 m, and the distance between the source and the calibration microphone $r_c = 1$ m. The reflecting surface was assumed to be absolutely rigid ($|Q| = 1$, $\Omega = 0$), $\kappa(f) = 1$, air temperature was 20°C, the relative humidity was 50%, and the atmospheric pressure was 1014 hPa.

According to Fig. 2*b*, at nonspherical DP of the source, the "modulation" of the interference "wave" occurs, which is not observed at the isotropic DP. An example of the processing of experimental results is shown in Fig. 3.



a *b*

Fig. 3. Comparison of experimental (asterisks) and theoretical (solid curves) results for a distance between the acoustic source and receivers of 13.6 m, the source height $h_s = 1.47$ m and the receiver heights $h_r = 2.61$ m (*a*) and $h_r = 1.48$ m (*b*). Experimental results are presented along with rms deviations shown as vertical bars. We assumed the complete coherence of the direct and reflected signals and the absolutely rigid surface ($|Q| = 1$, $\Omega = 0$).

The experiments were conducted at a relatively plain surface (roof) at a gentle breeze (0.2–1.5 m/s). We can state a good agreement between the experimental results and the theoretical calculations by Eq. (3), especially, at low frequencies. In addition to the agreement with interference "waves," the experimental data follows the "modulation" due to DP nonsphericity predicted by Eq. (3). Somewhat worse agreement between theory and experiment at high frequencies can be likely explained by a fall of the acoustic wave coherence with the increasing frequency due to turbulent pulsations of wind velocity and temperature, by idealization of impedance properties of the reflecting surface, and, possibly, by some other reasons. The neglect of this effect can lead to some errors in interpretation of experimental results connected with the study of the function $D(f, r_1, r_2, r_d, \theta_d, \theta_r)$.

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