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INFLUENCE OF THE PROPERTIES OF THE EARTH’S SURFACE ON SOUND WAVE PROPAGATION IN THE ATMOSPHERE

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Sound propagation near the ground has its own special features that differ from those for sound propagation in free space. First of all, this is caused by the fact that not only meteorological conditions (wind speed and direction, temperature, humidity, turbulence, and pressure) but also properties of the underlying surface influence sound propagation. In the present work, the influence of the underlying surface properties on sound attenuation is examined. Results of theoretical calculations with the use of the Delany–Basley model are compared with our experimental data.

The problem of sound propagation above the Earth’s surface has been studied most intensively all over the world in the last few years. The basic laws of near-ground sound propagation, the results obtained, and the models have been studied theoretically and experimentally in [1–10]. At present there exist the state and international standards on methods of calculating the sound attenuation during its near-ground propagation [11–13]. In addition to investigations of the influence of the meteorological conditions on the sound wave characteristics (the main of which is sound attenuation), attention is focused on the influence of the underlying surface properties, including its impedance properties and attenuation.

Let us consider sound propagation above the underlying surface whose geometry is shown in Fig. 1. At the reception point, the sum of two waves is observed, namely, the wave directly transmitted from the source to the receiver and the wave reflected from the Earth’s surface. The total sound pressure level at the reception point can be written as [9]

\[ p = p_d + R_p \cdot p_r, \]  (1)

where \( p_d \) takes into account the contribution of the directly transmitted wave, and \( p_r \) considers the contribution of the specularly reflected wave.

\[ \Delta \varphi = k \cdot (r_d - r_r) + \varphi, \]  (2)

where \( \varphi \) considers the phase change of the wave caused by its reflection from the underlying surface, \( r_d \) is the path length for the directly transmitted wave, and \( r_r \) is the path length for the reflected wave. The interference minima arise when the directly transmitted and reflected waves are in antiphase, and the interference maxima arise when they are in phase.

For a porous surface with \( 0 < \varphi < \pi \), the position of extremes in the received signal spectrum will depend on the experimental geometry and the coefficient of sound reflection from the underlying surface which can be written as
Because it is difficult to determine the reflecting layer thickness for the true underlying surface, the Earth’s surface is represented as a layer of semi-infinite thickness with a locally reflecting boundary surface. In this case, the sound reflection coefficient is written in the form

\[
R_p(\varphi) = \sin \varphi + \frac{Z_{\text{air}}}{Z_{\text{ground}}} \frac{Z_{\text{ground}}}{Z_{\text{air}}} \sin \varphi.
\]

where \(Z_{\text{air}}\) is the air impedance and \(Z_{\text{ground}} = R + i \cdot X\) is the characteristic impedance of the underlying surface.

In most cases, to solve problems of sound propagation above the underlying surface, the Delany–Basley model of the Earth’s surface impedance

\[
Z_c = \rho_0 \cdot c_0 \cdot \left(1 + 0.0571 \cdot \left(\frac{\rho_0 \cdot f}{\sigma}\right)^{-0.754} - i \cdot 0.087 \cdot \left(\frac{\rho_0 \cdot f}{\sigma}\right)^{-0.732}\right)
\]

is used. Here \(\rho_0\) is the air density, \(c_0\) is the sound speed in air, and \(\sigma\) is the effective flow resistivity.

For a spherical sound wave, both directly transmitted and reflected waves are additionally attenuated due to the so-called surface wave. In this case, the field at the reception point, by analogy with the theory of electromagnetic waves, is written in the form

\[
\frac{p}{p_0} = \frac{1}{r_d} \cdot e^{-i k r_d} + \frac{R_p}{r_r} \cdot e^{-i k r_r} + (1 - R_p) \cdot \frac{F(w)}{r_r} \cdot e^{-i k r_r},
\]

where \(p\) is the sound pressure level at the reception point, \(p_0\) is the source sound pressure level measured at a distance of 1 m, \(k = \frac{2 \cdot \pi \cdot f}{c}\) is the wave number, \(f\) is the sound frequency, \(c\) is the sound speed, \(r_d\) and \(r_r\) are distances from the source to the receiver and from the imaginary source to the receiver, respectively, \(R_p\) is the surface reflection coefficient, and \(F(w)\) is the coefficient of surface losses.

The first term in Eq. (6) describes the wave propagating from the source to the receiver. The second term of the equation describes the reflected wave. The first two terms determine a solution for a plane wave most strongly attenuated when \(\sin \varphi << \frac{Z_{\text{air}}}{Z_{\text{ground}}}\).

The third term of the equation describes the surface wave which characterizes the difference between the reflected plane wave and the spherical wave. The coefficient of surface losses that describes the interaction of the spherical wave front of incident radiation with the plane underlying surface is written in the form

\[
F(w) = 1 + 2 \cdot i \cdot \left(\frac{\pi \cdot w}{2}\right)^{\frac{1}{2}} \cdot e^{-w} \cdot \int_{-i \cdot w}^{\frac{1}{2}} e^{-u^2} du,
\]

where \(w\) is the numerical distance assigned under assumption of locally-reflecting boundary surface in the form
The attenuation coefficient caused by the Earth’s surface can be derived from Eq. (6):

\[
\alpha_{\text{ground}} = 20 \log \left[ 1 + \frac{R_p}{R_0} \cdot Q \cdot e^{i k (\sigma - \eta)} \right],
\]

(9)

where \( Q = R_p + (1 - R_p) \cdot F(w) \).

Equation (9) gives an efficient method of calculating sound attenuation by the Earth’s surface for the known Earth’s surface impedance as a function of the sound frequency. For a rigid underlying surface, \( \sigma = \infty \). The impedance of the underlying surface \( Z_{\text{ground}} \to \infty \), and reflection coefficient \( R_p \to 1 \). From Eq. (9) it follows that in this case, the attenuation by the underlying surface depends only on the sound propagation geometry and the radiation frequency.

For sound wave propagation above a porous surface, in addition to the phase shift between the directly transmitted and reflected waves, the phase shifts caused by reflection from the surface and influence of the coefficient of surface losses are added. It can be demonstrated that the main peculiarity caused by the reflection coefficient and surface losses is that \( \Delta \varphi(Q) \to \pi \). The given tendency will be clearly manifested at low \( \sigma \) values and at high frequencies for high \( \sigma \) values.

By way of example, Fig. 2 shows results of experimental investigations performed from the end of November, 2006 till June, 2007 at the test field of the Institute with an acoustic complex [12, 13].

![Fig. 2. Experimental dependence of the sound pressure level on the distance. The source was at a height of 6 m, and the receiver was at a height of 1 m. The sound frequency was 1000 Hz. The underlying surface represented the frozen ground with dried grass.](image)

The experimental setup comprised a transmitting system with a directed acoustic antenna and a receiving system with two Bruel&Kjer sound level meters. The first sound level meter was placed at the base point at a distance of 20 m from the transmitter, and the second sound level meter was subsequently transported at four measuring points at distances of 90, 180, 210, and 270 m from the transmitter. At each point, measurements were carried out with a microphone placed at heights of 0, 0.5, 1, and 1.5 m above the underlying surface. White noise was used as a useful signal. Measurements were carried out in 1/3-octave frequency ranges from 315 to 12500 Hz using 1/3-octave filters. The ultrasonic meteorological station, Zvuk-3 sodar, and standard meteorological sensors were used to support measurements. The transmitting antenna axis was at a height of 6 m...
above the ground. The underlying surface for the propagation path represented a smooth field with old dried grass and rare bushes up to 1 m high covered with snow in winter and grass in spring and summer.

The attenuation caused by the underlying surface was determined as a difference between the measured and calculated sound pressure levels. The measured values were averaged over a series of 3 successive measurements at each microphone height and fixed distance. Sound pressure levels at measurement points were calculated from the formula that took into account changes in the sound pressure level with allowance for the spherical divergence alone.

The difference between the measured and calculated sound pressure levels determined the excess attenuation at the measurement point that was then compared with the attenuation caused by the underlying surface and calculated from formula (9). Delany–Basley model (5) was used for the underlying surface model. The effective flow resistance $\sigma$ was taken from [14].

Results of our investigations demonstrated that on average, the results of theoretical calculations and measurements of sound attenuation by the underlying surface were in good agreement for frequencies in the range from 800 to 2000 Hz (the difference was 1–3 dB). At high frequencies, a large difference of about 10–15 dB was observed. The given tendency is primarily due to the fact that the effect of wind was not taken into account in our calculations.

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