TURBULENT ATTENUATION OF A SOUND WAVE PROPAGATING NEAR THE GROUND

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A technique is proposed for estimating the turbulent losses of a sound wave propagated in the surface atmospheric layer. The technique is based on the use of the expressions for coefficients of scattering by temperature and wind velocity fluctuations. These expressions have been derived using the von Karman model of the spectral density of the turbulent energy distribution.

Experimental studies of sound scattering by the atmospheric turbulence have shown that the coefficient of the excess turbulent attenuation varies over wide limits depending on the meteorological parameters. The sound scattering cross section is generally determined by the fluctuations of wind velocity at the scattering angles $\theta < 80°$, but at $\theta > 80°$ the temperature fluctuations should be taken into account. Data on the frequency dependence of the attenuation caused by the atmospheric turbulence are contradictory. The dependence proportional to the cubic root of the frequency is given in Ref. 1 and the quadratic frequency dependence is given in Ref. 2.

The theoretical analysis of sound scattering by the atmospheric turbulence is given in Ref. 3 in which the expression for the effective scattering cross section is derived for the inertial interval of turbulence, in addition, the inhomogeneities are assumed to be much less than the outer scale of the turbulence. The expression derived in Ref. 3 does not allow one to calculate the scattering phase function at small scattering angles because of the divergence of the integrand and to derive the coefficient of excess turbulent attenuation either. The expression for the coefficient of the excess attenuation is proposed in Ref. 4 in small–angle approximation which is commonly used in theory of optical wave propagation. However, the incorrect use of this method for the acoustic wave range by means of substitution of the condition $\lambda \ll l_0$ by the inadequate condition $\lambda \ll L_0$ for the acoustic range was noted in Ref. 5. Here, λ is the incident wavelength, l_0 is the inner scale, and L_0 is the outer scale of the atmospheric turbulence.

In this paper we propose the technique for estimating the attenuation losses due to atmospheric turbulence in the process of sound propagating in the surface layer of the atmosphere. This technique is based on the expressions for the coefficients of scattering by fluctuations of temperature[6] and wind velocity[7] which we have derived using the von Karman model of the spectral density of the turbulent energy distribution.

The attenuation losses due to turbulence in the process of propagating the sound wave along the near–surface path from a transmitter to a receiver can be represented in the form

$$L_T = \exp\left\{ \int\limits_0^R \beta_{TV}(r, F, L_0, c_T, T, c_V)\, \mathrm{d}r \right\}, \qquad (1)$$

where $R = \sqrt{d^2 + (h_t - h_r)^2}$ is the length of the propagation path, d is the distance between the transmitter and the receiver, h_t and h_r are the heights of the transmitter and receiver above the ground, respectively; T is the air temperature; F is the acoustic radiation frequency; r is the running coordinate along the propagation path; c_T and c_V are the structure characteristics of the fluctuations of the temperature and wind velocity, respectively;

$$\beta_{TV}(r, F, L_0, c_T, T, c_V) = \beta_T(r, F, L_0, c_T, T) + \beta_V(r, F, L_0, c_V) \qquad (2)$$

is the total coefficient of turbulent attenuation; β_T and β_V are the coefficients of scattering by the fluctuations of the temperature and the wind velocity, respectively, which are given by the formulas

$$\beta_T = 0.9\lambda^{-1/3} c_T^2 T^{-2} L_2^{-7/3} [0.0714(B^{7/6} - \lambda^{7/3}) - 0.1A^2(B^{-5/6} - \lambda^{-5/3}) - A(B^{1/6} - \lambda^{1/3})] ;$$

$$\beta_V = 2.982 c_V^2 \lambda^{-1/3} c^{-2} L_0^{-13/3} [0.1429(B + 2A)(B^{7/6} - \lambda^{7/3}) - 0.0769(B^{13/6} - \lambda^{13/3}) - A(A + 2B)(B^{1/6} - \lambda^{1/3}) - 0.2A^2B(B^{-5/6} - \lambda^{-5/3})] . \qquad (3)$$

Here λ is the acoustic wavelength, c is the speed of sound, $A = 2L_0^2 + \lambda^2$, and $B = 4L_0^2 + \lambda^2$.

The input parameters of the technique for estimating the attenuation losses due to turbulence are: the length of the propagation path R, the maximum of the heights of the transmitter and receiver location $h_{max} = \{h_t, h_r\}$, as well as the measured or estimated values of the structure characteristics of temperature and wind velocity in the surface atmospheric layer. Calculations were performed for $h_{max} = 8$ m which allowed us to neglect the altitude dependence of c_T^2 and c_V^2 and use their values for the surface layer taken from Refs. 8 and 4: for strong turbulence $c_T^2 = 0.9$ m$^{-2/3}$K^2 and $c_V^2 = 0.1$ m$^{4/3}$s^{-2}, and for weak turbulence $c_T^2 = 0.02$ m$^{-2/3}$K^2 and $c_V^2 = 0.01$ m$^{4/3}$s^{-2}. Attenuation due to turbulence in dB can be written as $L_T(\mathrm{dB}) = 10 \log P_0/P = 10 \log L_T$, where P and P_0 are the powers of the received and transmitted signals. A comparison between the frequency dependence of attenuation due to turbulence according to the experimental data of Ref. 9 and the results of calculation according to the proposed technique are shown in Fig. 1.

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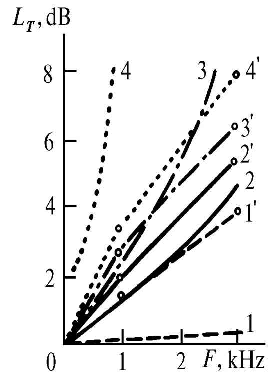

FIG. 1. Frequency dependence of the attenuation due to turbulence: curves 1 (calculated) and 1′ (experimental) are for R = 154 m *and* h_{max} = 1.5 m; *curves 2 (calculated) and 2′ (experimental) are for* R = 250 m *and* h_{max} = 5 m; *curves 3 (calculated) and 3′ (experimental) are for* R = 375 m *and* h_{max} = 6 m; and, *curves 4 (calculated) and 4′ (experimental) are for* R = 835 m *and* h_{max} = 8 m.

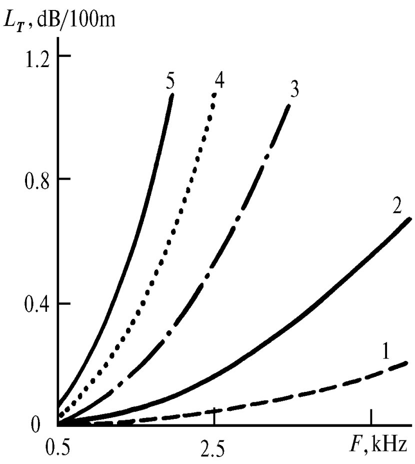

FIG. 2. Turbulent attenuation for strong turbulence and h_{max} = 1 m *(1),* 2 m *(2),* 4 m *(3),* 6 m *(4), and* 8 m *(5).*

As can be seen from the figure the calculated dependence of L_T for the indicated values of R does not always satisfactorily agree with the experimental results. We can explain the observed disagreement between the calculated and experimental data by the fact that the value of c_n^2 was not monitored during the experiment.

The experimental frequency behavior satisfactorily agreed with the theoretical one for $h_{\max}$ = 5 m and R = 250 m (curves *2* and *2′*). Substantial difference increasing with frequency can be found in other cases. The experimentally measured attenuation for $h_{\max}$ = 1.5 m (curves *1* and *1′*) is larger than that theoretically calculated and the significant disagreement can be probably explained by the effect of the adjacent ground. The theoretical calculations show that the frequency dependence of attenuation due to turbulence slopes more steeply than it follows from the experimental data for $h_{\max}$ = 6 m and R = 375 m (curves *3* and *3′*) as well as for $h_{\max}$ = 8 m and R = 835 m (curves *4* and *4′*).

The results of calculation of L_T for the fixed $h_{\max}$ and weak turbulence in the 500–5000 Hz frequency range show that the losses caused by turbulence does not exceed 0.004 dB/100 m under the given conditions, i.e., attenuation due to turbulence can be neglected.

The frequency dependences of attenuation due to turbulence calculated for strong turbulence are shown in Fig. 2. For the frequencies $F < 1$ kHz, L_T is less than dissipative losses on the examined paths. For $h_{\max} < 1$ m the value of L_T is less by several times than the losses due to the molecular absorption. Hence, attenuation due to turbulence can be neglected for frequencies lower than 1 kHz and for heights of the transmitter and receiver location less than 1 m. However, for $h_{\max}$ = 8 m even at F = 1.5 kHz the value of L_T is significant.

In conclusion it should be noted that neglecting the excess turbulent attenuation of signal on the path can lead to the large errors in solving the sound propagation problem. The above–presented estimates according to the proposed technique do not always allow us to predict unambiguously the sound attenuation due to turbulence and its frequency dependence under the specific conditions. To this end, more careful experimental studies must be carried out.

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