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Influence of turbulence on train noise

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ABSTRACT

The subject of this paper is the long distance propagation of train noise. The sound exposure level of train noise L_{AE} was measured. To describe the results of measurements, a semi-analytical model was used. It takes into account the wave-front divergence, air absorption, ground effect, and the turbulence destroying the coherent nature of the ground effect. The model contains three adjustable parameters that must be estimated at the site. To verify the model, we performed measurements of L_{AE} at the distance D = 450 m from the train track center. The difference between the calculated and measured mean values of L_{AE} equals 1.3 dB.

1. Introduction

In outdoor noise the propagation is affected by the following wave phenomena: wave-front divergence, air absorption, ground effect, diffraction at obstacles, sound interaction with atmospheric turbulence and refraction. Rigorous solutions are both experimentally and numerically difficult, although tremendous progress has been made in understanding the nature of wave propagation and powerful computational facilities have been widespread [1]. For a routine noise prediction, it is desirable to use a model of noise propagation that is simple enough, yet reveals the main features of all wave phenomena under consideration. The ISO-9613 [2] is the best known example. Ref. [3] presents a comparison between the best known European prediction models of the rail traffic noise. In Ref. [4], a simple model was proposed taking into account the wave-front divergence and ground effect by the parameter γ. Then, air absorption has been included [5] by an additional attenuation given by $10\log(1+\alpha d)$, where α represents the air absorption coefficient. Finally the turbulence effects, characterized by an additional parameter $\sigma = \beta$, has been incorporated [6,7]. The model used in this study has been already confirmed experimentally [1]. Examples of applications to road vehicle, industrial and train noise can be found in papers [8–12].

In this study, a model is used to derive an equation for the sound exposure level L_{AE} of train noise. Introducing the coefficients related to air absorption (α), ground effect (γ, k), and turbulence (β), the explicit form of the function $L_{AE}(H_s, H_o, D)$, where H_s, H_o and D describe the source–receiver geometry, is derived (Fig. 1).

Compared to other well known railway noise prediction models (especially the accurate numerical methods) the presented here model is much simpler. It needs only three adjustable parameters which describe the ground effect, the air absorption and the atmospheric turbulence. Additionally in this paper the method of the model's parameters estimation is presented.

2. Theory

The railway noise is assessed in terms of the sound exposure level,

$$L_{AE} = 10\log\left(\frac{E_A}{p_o^2 t_o}\right), \tag{1}$$

where p_o = 20 μPa and t_o = 1 s. At a speed less than 250 km/h, the main source of noise generated by a train is the wheel-rail interaction [13]. This kind of noise can be modeled by a homogeneous line of incoherent point sources [13,14].

For a train moving at a constant speed V along the x-axis at the perpendicular distance D (Fig. 2) the sound exposure can be written as

$$E_A = \frac{Dl}{V}\int_{-\pi/2}^{+\pi/2} \frac{p_A^2(\Phi)}{\cos^2\Phi}\, d\Phi, \tag{2}$$

where p_A^2 is the A-weighted squared sound pressure of noise, due to the unit length line source (l_o = 1 m) and l is the length of train. The limits of integration, $\pm\pi/2$, hold when the whole track is heard at the receiver (downwind refraction).

If p_{A0}^2 quantifies the wave-front spreading (Section 2.1), F_A describes the air absorption (Section 2.2), and G_A characterizes

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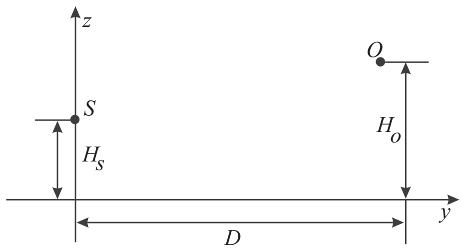

Fig. 1. Source–receiver geometry in vertical plan.

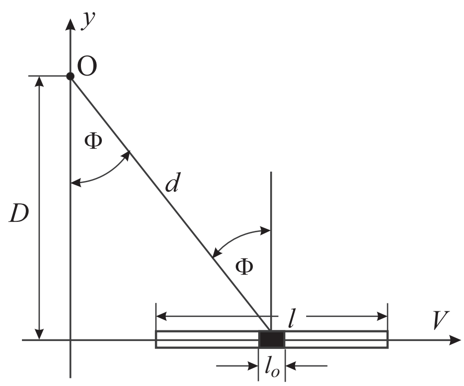

Fig. 2. Train–receiver geometry in the horizontal plane.

the ground effect (Section 2.3) modified by turbulence (Section 2.4), the sound exposure can be calculated from:

$$E_A = \frac{Dl}{V}\int_{-\pi/2}^{+\pi/2}\frac{p_{A0}^2(\Phi)}{\cos^2\Phi}F_A(\Phi)G_A(\Phi)d\Phi. \quad (3)$$

2.1. Wave-front divergence

Under free field conditions, the A-weighted squared sound pressure of noise, due to the unit length line source ($l_o = 1$ m), may be written as:

$$p_{A0}^2 = \frac{W_A \cdot Q(\Phi)\rho c}{4\pi d^2}, \quad (4)$$

where W_A in W m^{-1} denotes the A-weighted sound power of the unit length line source, ρc is the characteristic impedance of air, d is the instantaneous source–receiver distance, and $Q(\Phi)$ describes the noise radiation in the direction determined by the angle Φ. For near grazing propagation, $H_s + H_o \ll D$, with $d = D/\cos\Phi$ (Fig. 2), the sound exposure can be calculated from

$$E_A = \frac{lqW_A\rho c}{DV}, \quad (5)$$

where the source directivity is characterized by

$$q = \frac{1}{4\pi}\int_{-\pi/2}^{+\pi/2}Q(\Phi)d\Phi. \quad (6)$$

Consequently, the definition (1) leads to the sound exposure level:

$$L_{AE} = \widetilde{L}_{WA} + 10 \cdot \log\left(\frac{ll_o}{DVt_o}\right), \quad l_o = 1\text{ m}, \quad (7)$$

where

$$\widetilde{L}_{WA} = 10 \cdot \log\left(\frac{qW_A}{W_o}\right), \quad W_o = 10^{-12}\text{ W}, \quad (8)$$

denotes the "effective" sound power level of the unit length line source changed by the source directivity (q).

2.2. Air absorption

Air absorption modifies the sound pressure amplitude of the wave. For a nondirectional point source in open space, the A-weighted squared sound pressure is given by

$$p_A^2 = \frac{W_A\rho c}{4\pi d^2} \cdot F_A(d, T, RH), \quad (9)$$

where

$$F_A = \sum_n 10^{\delta L_n/10} \cdot 10^{A_n \cdot d/1000} \quad (10)$$

expresses the A-weighted air absorption factor. The quantity $A_n(T, RH)$ is the standardized attenuation coefficient (in dB/km) at the pressure of 1013.25 hPa, which depends on the air temperature T °C, and relative humidity RH % [15] and δL_n is the referenced A-weighted power level. In our analysis we made use of the referenced power spectrum given in Ref. [16]. It is "typical of roadway, aircraft and rail traffic" (Fig. 3). The exact noise attenuation due to air absorption can be approximated by simpler formula [17]:

$$F_A = [1 + \alpha(T, RH) \cdot d]^{-1}. \quad (11)$$

When $d \to 0$, the influence of air absorption disappears and $F_A \to 1$ (the same result can be obtained for $\alpha \to 0$). The values of the equivalent absorption coefficient α (in m^{-1}) were calculated for different temperatures T, and different relative humidities RH, with the referenced power spectrum. The results in Fig. 4 show the temperature and humidity of maximum and minimum air absorption. We assume that weak and strong air absorptions correspond to $\alpha = 3.5 \cdot 10^{-4}$ m^{-1} and $\alpha = 70 \cdot 10^{-4}$ m^{-1}, respectively. The changes of air attenuation, expressed in terms of $10 \cdot \log(F_A)$ are plotted in Fig. 5.

Expression (11) approximates the exact air absorption factor F_A (Eq. (10)) within 1.0 dB at a distance $d < 500$ m. Substituting Eq. (11) into (9) one gets

$$p_A^2 = \frac{W_A\rho c}{4\pi r^2} \cdot \frac{1}{1 + \alpha(T, RH) \cdot d}. \quad (12)$$

Note, that the above equation neglects the ground effect, i.e. it is correct high above the ground surface.

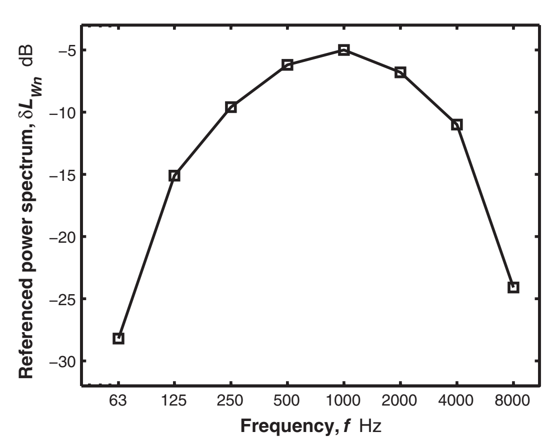

Fig. 3. The referenced power spectrum, $L_{Wn} - L_{WA}$ [16].