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INDUSTRIAL NOISE FROM A POINT SOURCE

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A simple method is presented that requires measurements at only two positions. It can be used for the prediction of the time-averaged sound level, L_{AT}, above a plain and homogeneous ground surface, in open space with no obstacles nearby. Upward and downward conditions are addressed, in addition to geometrical spreading and ground effect. The method makes it possible to predict L_{AT} at the receiver, located beyond the shadow zone that is caused by upward refraction.

1. INTRODUCTION

Weather conditions, principally wind, have major effects on noise propagation in the atmosphere. The present study demonstrates how to predict the time-averaged sound level, L_{AT}, at horizontal distance from the source, d, and at height above the ground surface, z, when the results of noise measurements at two points, $O(d_1, z_1)$ and $O(d_2, z_2)$, are available (see Figure 1).

Related (but not equivalent) analyses of the outdoor noise propagation problem have been reported in Piercy and Daigle [1], Anderson and Kurze [2], and ISO Standard 9613 [3]. The methods presented therein take into account the influence of weather. In the present study three categories of propagation conditions are introduced and the number of free parameters of the model is minimized. Consequently, the prediction method becomes relatively simple and useful for practical purposes (see Example IV in section 4).

Suppose that during the time period τ (e.g., 2 h), a stationary source (e.g., cooling tower, ventilation fan, transformer, jackhammer, or cement mixer) produces noise. The time-average sound level L_{AT}, during the time period T (e.g., 15 hours of a day) is

$$L_{AT} = 10 \log \{(\tau/T)S + 10^{\tilde{L}_{AT}/10}\}, \tag{1}$$

where $\tilde{L}_{AT}$ is the time-averaged sound level of background noise. Upon introducing the A-weighted sound pressure, p_A, the relative time-averaged A-weighted squared sound pressure can be written as

$$S = \frac{1}{\tau}\int_0^\tau \frac{p_A^2(t)}{p_0^2}\,\mathrm{d}t, \qquad p_0 = 20\ \mu\ \mathrm{Pa}. \tag{2}$$

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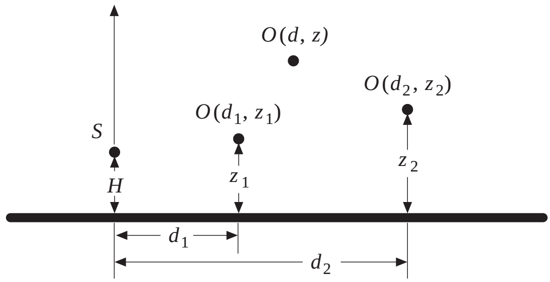

Figure 1. Location of measuring microphones (d_1, z_1) and (d_2, z_2).

During the time period τ, when the source is active, one can expect at least three categories of propagation conditions [4]: straight rays due to a homogeneous and calm atmosphere; downward bending of rays due to wind blowing from the source to the receiver and/or temperature increase upward; upward bending of rays due to wind blowing from the receiver to the source and/or temperature decrease upward. For the time intervals τ_0, τ_1, and τ_2, corresponding to these conditions (see Figure 2), equation (2) takes the form

$$S = (\tau_0/\tau)S_0 + (\tau_1/\tau)S_1 + (\tau_2/\tau)S_2, \tag{3}$$

where

$$S_0 = \frac{1}{\tau_0}\int_0^{\tau_0} \frac{p_{A0}^2}{p_0^2}\,\mathrm{d}t, \qquad S_1 = \frac{1}{\tau_1}\int_0^{\tau_1} \frac{p_{A1}^2}{p_0^2}\,\mathrm{d}t, \qquad S_2 = \frac{1}{\tau_2}\int_0^{\tau_2} \frac{p_{A2}^2}{p_0^2}\,\mathrm{d}t. \tag{4}$$

To avoid complications and to show clearly only the main ideas, one can apply very restrictive assumptions: a non-directional point source generates a stationary broadband noise; noise propagates freely above a plain and homogeneous ground surface; and geometrical spreading and ground effect are modified mainly by refraction.

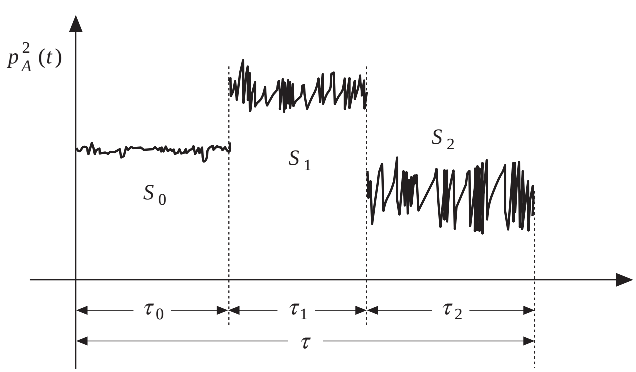

Figure 2. The A-weighted squared sound pressure, p_A^2, for homogeneous and calm atmosphere, τ_0, downward refraction, τ_1, and upward refraction, τ_2, which is drawn for illustrative purposes.

2. HOMOGENEOUS AND CALM ATMOSPHERE

Consider first the ground effect. The squared sound pressure in the nth frequency band, high above the ground with a non-dissipative and homogeneous medium, is

$$p_n^2 = W_n \rho c / 4\pi r^2, \tag{5}$$

where W_n denotes the corresponding sound power, ρc expresses the characteristic impedance of air, and r is the source–receiver distance. To describe the propagation of industrial noise, it is assumed that the point source, S, and the receiver, O, are close to the ground surface (see Figure 3), so that

$$z + H \ll d. \tag{6}$$

Under such conditions one can write

$$p_n^2 = (W_n \rho c / 4\pi r^2) G_n(d, z, H, Z_n), \tag{7}$$

where the ground factor, G_n, is given by [5, 6] as,

$$G_n = 1 + (r^2/r_1^2)[q_1^2 + q_2^2] + 2(r/r_1)[q_1 \cos(2\pi f_n \Delta r/c) + q_2 \sin(2\pi f_n \Delta r/c)], \tag{8}$$

The sum, $q = q_1 + iq_2$, expresses the spherical wave reflection coefficient, $\Delta r = r_1 - r$ denotes the difference between the path lengths of the direct and reflected waves (see Figure 3), and Z_n is the ground impedance in the nth frequency band. The validity of the above expression has been fully confirmed [7]. From equation (7) one arrives at the sound level,

$$L_A^{(0)} = L_{WA} - 10 \log\{2\pi d^2/d_0^2\} + 10 \log\{G_A\}, \quad d_0 = 1 \text{ m}, \tag{9}$$

where L_{WA} is the A-weighted power level, and the A-weighted ground factor is quantified by

$$G_A = \frac{1}{2} \sum_n 10^{(L_{Wn} - L_{WA} + \Delta L_n)/10} G_n(d, z, H, Z_n), \tag{10}$$

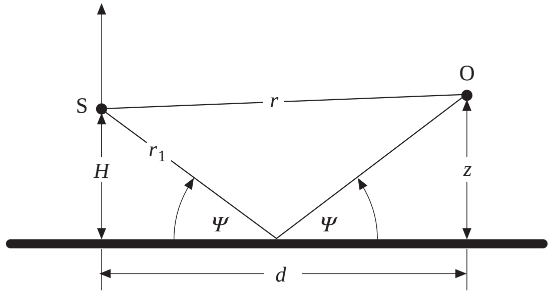

Figure 3. Source–receiver geometry (SO) is determined by the horizontal distance, d, and heights, z, H, or the grazing angle, Ψ.

with ΔL_n defining the A-frequency weighting. The results presented in Figure 9 of reference [8] indicate that the ground factor, G_n, is a function of the grazing angle (see Figure 3),

$$\Psi = \tan^{-1}[(z+H)/d]. \tag{11}$$

Thus, equation (10) can be rewritten as

$$G_A = G_A([z+H]/d). \tag{12}$$

Close to the source one obtains,

$$\lim_{d\to 0} G_A = G_A(0) = \beta. \tag{13}$$

Note that $\beta = 2$ for hemispherical spreading. The calculation shows that far away from the source, the ground attenuation decreases by 6 dB per doubling of the distance [6, 7], so one can write

$$\lim_{d\to\infty} G_n \propto d^{-2}. \tag{14}$$

The above result has been justified experimentally in equation (1) of reference [9]. Combining equations (12) and (14) yields

$$\lim_{d\to\infty} G_A = (1/\gamma_0)([z+H]/d)^2. \tag{15}$$

(Note the superscript 0 for the homogeneous and calm atmosphere).

The most simple function that meets both conditions given by equations (13) and (15) is

$$G_A = \beta[1+\gamma_0(d/[z+H])^2]^{-1}, \quad 0 \leqslant d \leqslant \infty, \tag{16}$$

where γ_0 is the ground coefficient and the source and/or receiver has to be above ground, $z+H>0$. Finally, the sound level for homogeneous and calm atmosphere can be approximated by (equations (9, 16))

$$L_A^{(0)} = 10\log\{Q_0\} - 10\log\{2\pi d^2/d_0^2[1+\gamma_0 d^2/(z+H)^2]\}, \tag{17}$$

where the source parameter, Q_0, and the ground coefficient, γ_0, have to be estimated from measurements (see below). In section 3 the influence of refraction and turbulence on the ground coefficient is demonstrated. Because the source is stationary and the atmosphere is calm, the sound level, $L_A^{(0)}$, equals the time-averaged sound level, $L_{A\tau}^{(0)}$.

Equation (17) is based on the well established theory of Weyl and Van der Pol [5] and fits the results of noise measurements above different ground surfaces. For illustration, the values of $L_A^{(0)}$ (equation (17)) are plotted versus the horizontal distance, d, with $Q_0 = 10^{10}$ and $z = H = 1$ m in Figure 4. For $\gamma_0 = 0{\cdot}0003$, one has a 7·5 dB drop per doubling of the distance, 50→100 m. This is typical for ground covered with grass or other vegetation [10]. With $\gamma = 0{\cdot}0009$, one has a 9 dB drop of the sound level per doubling of the distance (e.g., ground covered with snow).

In the present study, the source parameter, Q_0, and the ground coefficient, γ_0, are considered free parameters. How are values estimated from noise measurement

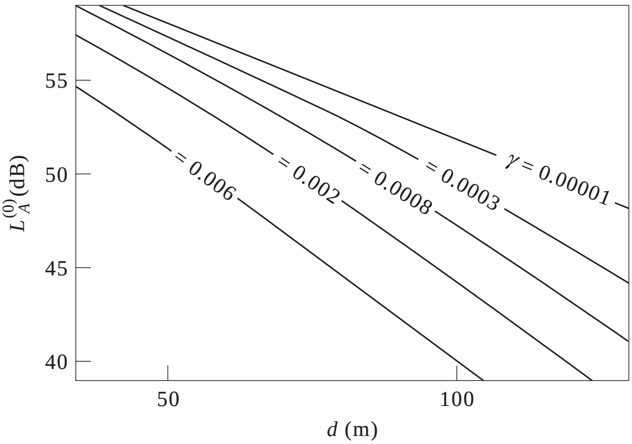

Figure 4. The sound level, $L_A^{(0)}$ versus horizontal distance d, for different values of ground coefficient, γ (equation (17)).

at the site of interest? Equation (17) holds when the atmosphere is homogeneous and calm, so the time-averaged sound level at the point $O(d_i, z_i)$ is given by

$$L_{A\tau}^{(i)} = 10 \log \{Q_0\} - 10 \log \{(2\pi d_i^2/d_0^2)[1 + \gamma_0 d_i^2/(z_i + H)^2]\}. \tag{18}$$

Making use of two measurements at the points, $O(d_1, z_i)$ and $O(d_2, z_2)$ (see Figure 1), one arrives at

$$\gamma_0 = (m-1)(z_1 + H)^2(z_2 + H)^2/[(z_1 + H)^2 d_2^2 - m(z_2 + H)^2 d_1^2], \tag{19}$$

where

$$m = (d_1/d_2)^2 10^{(L_{A\tau}^{(1)} - L_{A\tau}^{(2)})/10}. \tag{20}$$

By substituting γ_0 into equation (18) one obtains the source parameter, Q_0. Both γ_0 and Q_0 depend upon the power spectrum of the source. Hence, one can expect different values of γ_0 and Q_0 for cooling towers, ventilation fans, transformers, etc., and different ground coverings (grass, sand, etc.).

Example I. Noise produced by a cement mixer was measured at the distances $d_1 = 25$ m and $d_2 = 50$ m with the microphones at the same height, $z_1 = z_2 = 1$ m, above the ground covered by grass. The effective source height was $H \approx 2$ m. During the one hour that measurements were made, the atmosphere was calm (no wind) and the sky was cloudy (neither thermal turbulence nor temperature gradient within a few meters above the ground). With $\tau = 3600$ s, the results of the measurements were: $L_{A\tau}^{(1)} = 65{\cdot}1$ dB and $L_{A\tau}^{(2)} = 58{\cdot}8$ dB. The background noise level was fluctuating around 45 dB. By using equations (18–20), the values $\gamma_0 = 3{\cdot}26 \times 10^{-4}$ and $Q_0 = 1{\cdot}29 \times 10^{10}$ were obtained.

3. INFLUENCE OF REFRACTION

Due to weather variations influencing refraction, the dependence of the sound level, L_A, upon the horizontal distance, d, changes with time. To describe this effect, it is assumed that the ground coefficient becomes a function of time, $\gamma_0 \rightarrow \gamma(t)$, and equation (17) takes the form

$$L_A(t) = 10 \log \{Q\} - 10 \log \{2\pi d^2/d_0^2[1 + \gamma(t)/\tilde{\gamma}]\}, \tag{21}$$

where

$$\tilde{\gamma} = (z + H)^2/d^2. \tag{22}$$

This equation will be applied for both downward and upward refraction.

3.1. DOWNWARD REFRACTION

When sound propagates downward (e.g., wind blowing from the source to the receiver), within the time period τ_1 (see Figure 2), frequently the values of $\gamma(t)$ are less than the ground coefficient for a homogeneous and calm atmosphere, γ_0, and $L_A(t) > L_A^{(0)}$ (equations 17, 21). For example, if the rays bending toward the ground compensate for the ground attenuation, then $\gamma = 0$. One cannot exclude sound focusing with $L_A \rightarrow \infty$, which corresponds to $\gamma \rightarrow -\tilde{\gamma}$. Despite downward propagation "on average", there is some probability that $L_A(t) < L_A^{(0)}$, which is described by $\gamma > \gamma_0$. Suppose the density function of the random variable, γ, for the downward refraction is $f_1(\gamma)$. To calculate the relative time-averaged A-weighted squared sound pressure (equation 4), one can make use of the equality [11],

$$\frac{1}{\tau_1} \int_0^{\tau_1} \frac{p_{A1}^2(t)}{p_0^2}\, \mathrm{d}t = \int_{-\tilde{\gamma}}^{\infty} \frac{p_{A1}^2(\gamma)}{p_0^2} f_1(\gamma)\, \mathrm{d}\gamma, \tag{23}$$

and arrive at (equation (21))

$$S_1 = Q_1 \frac{d_0^2}{2\pi d^2} \int_{-\tilde{\gamma}}^{\infty} \left[1 + \frac{\gamma}{\tilde{\gamma}}\right]^{-1} f_1(\gamma)\, \mathrm{d}\gamma. \tag{24}$$

The mean value theorem of integral calculus [12] yields

$$\int_{-\tilde{\gamma}}^{\infty} \left[1 + \frac{\gamma}{\tilde{\gamma}}\right]^{-1} f_1(\gamma)\, \mathrm{d}\gamma = \left[1 + \frac{\gamma_1}{\tilde{\gamma}}\right]^{-1}, \tag{25}$$

where γ_1 is the weather coefficient for downward refraction. Finally, the time-averaged sound level, $L_{A\tau} = 10 \log \{S_1\}$, becomes (equations (22, 24, 25))

$$L_{A\tau} = 10 \log \{Q_1\} - 10 \log \{2\pi d^2/d_0^2[1 + \gamma_1 d^2/(z + H)^2]\}. \tag{26}$$

To estimate numerical values for Q_1 and γ_1, two measurements of $L_{A\tau}$ under downward conditions of propagation are needed (equations (19, 20, 26)). Note that the numerical value of γ_1 accounts for ground effect, refraction and wind eddies, i.e., atmospheric turbulence.

Example II. Noise, produced by the same cement mixer as in Example I, was measured at the distances $d_1 = 25$ m and $d_2 = 50$ m and the heights $z_1 = z_2 = 1$ m. Due to wind blowing toward the microphones, there were the downward conditions of sound propagation. For the sample time $\tau = 1$ h, the results are: $L_{A\tau}^{(1)} = 66{\cdot}6$ dB and $L_{A\tau}^{(2)} = 60{\cdot}4$ dB. The background noise level was below 50 dB. Equations (19), (20), and (26) yield the weather coefficient, $\gamma_1 = -1{\cdot}44 \times 10^{-4}$ (note the negative value) and the source parameter, $Q_1 = 1{\cdot}80 \times 10^{10}$.

3.2. UPWARD REFRACTION

During upward propagation (e.g., wind blowing from receiver to the source), the average value of the sound level, $L_A(t)$ (equation (21)), is lower than that for neutral conditions of propagation, $L_{\rm A}^{(0)}$. Large fluctuations, however, may occur. Thus, similarly to the case of downward refraction considered above, one assumes that the random variable, γ, changes from $-\tilde{\gamma}$ to $+\infty$. The distribution function for downward refraction is $f_1(\gamma)$. There is no evidence, however, that for upward refraction the same distribution function remains. Therefore one can introduce $f_2(\gamma)$ and obtain (equation (24))

$$S_2 = Q_2 \frac{d_0^2}{2\pi d^2} \int_{-\tilde{\gamma}}^{\infty} \left[1 + \frac{\gamma}{\tilde{\gamma}}\right]^{-1} f_2(\gamma)\,\mathrm{d}\gamma. \tag{27}$$

Finally, one arrives at the time-averaged sound level,

$$L_{A\tau} = 10 \log \{Q_2\} - 10 \log \{2\pi d^2/d_0^2[1 + \gamma_2 d^2/(z + H)^2]\}, \tag{28}$$

where Q_2 is the source parameter and γ_2 is the weather parameter for upward refraction. The above equation holds when the receiver is beyond the shadow zone. To estimate the numerical values of Q_2 and γ_2, two measurements of $L_{A\tau}$ are necessary (equations (19, 20, 28)).

Example III. At the same points used in Examples I and II, simultaneous measurements were carried out of the time-averaged sound level, $L_{A\tau}$, with the sample time $\tau = 1$ h. This time, however, wind was blowing toward the cement mixer. With the background noise level fluctuating around 47 dB, $L_{A\tau}^{(1)} = 64{\cdot}2$ dB and $L_{A\tau}^{(2)} = 57{\cdot}3$ dB were obtained. Equations (19), (20), and (28) give the source parameter $Q_2 = 1{\cdot}12 \times 10^{10}$, and the weather coefficient $\gamma_2 = 1{\cdot}16 \times 10^{-3}$.

4. CONCLUSIONS

If the conditions of sound propagation listed in the Introduction prevail during the time intervals τ_0, τ_1, and τ_2, respectively, then the time-average sound level, $L_{A\tau}$, with the sample time, $\tau = \tau_0 + \tau_1 + \tau_2$ (see Figure 2), can be calculated from (equations (3, 17, 26, 28))

$$L_{A\tau} = L_A^{(0)}(d, z) + \Delta L_{A\tau}(d, z), \tag{29}$$

where $L_A^{(0)}$ (equation (17)) is the sound level for a homogeneous and calm atmosphere, and the refraction influence is accounted by

$$\Delta L_{A\tau} = 10 \log \{1 - P_1 F_1(d, z) - P_2 F_2(d, z)\}. \tag{30}$$

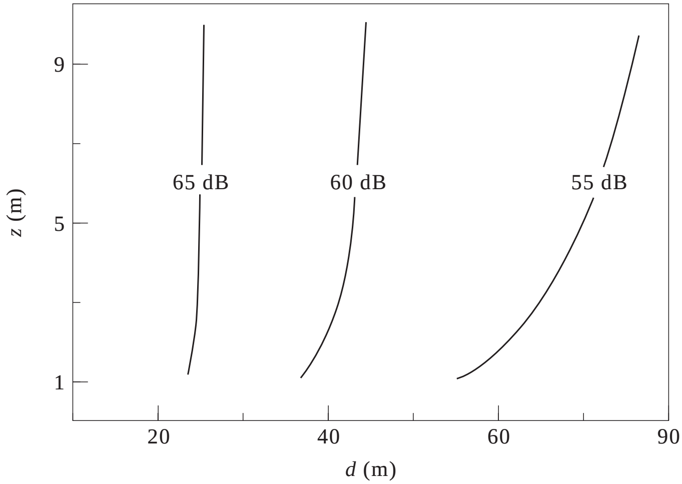

Figure 5. Contours of L_{A15h} = const. calculated from equations (34–37).

Here, $P_1 = \tau_1/\tau$ and $P_2 = \tau_2/\tau$ denote the probabilities of the downward, and upward refraction, and

$$F_1 = 1 - \frac{Q_1}{Q_0}\frac{(z+H)^2 + \gamma_0 d^2}{(z+H)^2 + \gamma_1 d^2}, \qquad F_2 = 1 - \frac{Q_2}{Q_0}\frac{(z+H)^2 + \gamma_0 d^2}{(z+H)^2 + \gamma_2 d^2}. \tag{31}$$

If the value of $L_{A\tau}$ (equation (29)) for industrial noise is known and the time-averaged sound level of background noise, $\tilde{L}_{AT}$, is available, then the noise during the time interval, $T > \tau$, can be assessed by (equation (1))

$$L_{AT} = 10 \log \left\{ \frac{\tau}{T} 10^{L_{A\tau}(d,\,z)/10} + 10^{\tilde{L}_{AT}/10} \right\}. \tag{32}$$

Example IV. The following results of measurements and calculations from Examples I, II, and III: $\gamma_0 = 3{\cdot}26 \times 10^{-4}$, $Q_0 = 1{\cdot}29 \times 10^{10}$; $\gamma_1 = -1{\cdot}44 \times 10^{-4}$, $Q_1 = 1{\cdot}80 \times 10^{10}$ and $\gamma_2 = 1{\cdot}16 \times 10^{-3}$, $Q_2 = 1{\cdot}12 \times 10^{10}$. Suppose the cement mixer is working $\tau = 5$ h during a day and the probabilities of downward and upward refraction are $P_1 = 0{\cdot}2$ and $P_2 = 0{\cdot}1$. For the background noise, $\tilde{L}_{AT} = 48$ dB, the day time-averaged sound level, L_{A15h}, with $T = 15$ h, is (equation (32))

$$L_{A15h}(d, z) = 10 \log \{(5/15)10^{L_{A5h}/10} + 10^5\}, \tag{33}$$

where (equations (17, 29–31)),

$$L_{A5h} = 101{\cdot}1 - 10 \log \{2\pi d^2/d_0^2[1 + 3{\cdot}26 \times 10^{-4} d^2/(z+2)^2]\} + \Delta L_{A5h}, \tag{34}$$

with

$$\Delta L_{A5h} = 10 \log \{1 - 0{\cdot}2F_1 - 0{\cdot}1F_2\}, \tag{35}$$

and

$$F_1 = 1 - 1{\cdot}4\,\frac{(z+2)^2 + 3{\cdot}26 \times 10^{-4}d^2}{(z+2)^2 - 1{\cdot}44 \times 10^{-4}d^2},$$

$$F_2 = 1 - 0{\cdot}87\,\frac{(z+2)^2 + 3{\cdot}26 \times 10^{-4}d^2}{(z+2)^2 + 1{\cdot}16 \times 10^{-3}d^2}. \tag{36}$$

The contours of $L_{A15h}(d, z) =$ const. are shown on Figure 5.

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