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Influence of Atmospheric Turbulence on Sound Reduction by a Thin, Hard Screen: A Parameter Study Using the Sound Scattering Cross-section

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Summary

A prediction scheme is presented that uses a small number of pre-calculated data to predict the energy scattered by the turbulence and the diffracted energy for a large variety of situations with a thin, hard screen in the absence of a ground surface. This is done by applying transformations for variations in frequency and in geometrical scale, for both the scattered and the diffracted energies.

The influence of the turbulence scattering on the sound reduction by a screen is shown to grow when the geometry is increased in scale or when the frequency is increased. Moreover, the influence of the scattering grows when the screen-receiver distance is increased, and the weak scattering at angles near 90° leads to a dip in the influence of the scattering when the screen height is increased.

An example calculated for one geometry and with a typical traffic noise spectrum as input shows that taking onto account atmospheric turbulence can significantly reduce the performance of a noise barrier, not only at high frequencies, but also when measured in dB(A).

A three-dimensional integration of the scattered energy is shown to be simplified by an analytical integration in one dimension, which makes the numerical solution far quicker.

1. Introduction

To correctly predict the sound reduction by a noise barrier in an outdoor environment, the fact that the atmosphere is never homogeneous cannot be ignored. Wind and temperature gradients cause curved ray paths and the atmospheric turbulence causes scattering and decorrelation of the sound waves. The scattering has been shown to cause an increased sound energy in the acoustic shadow formed by upward refraction (e.g. [1]). In a similar way the scattering reduces the performance of a noise barrier [2, 3]. Especially for high frequencies and large scale geometries, the turbulence scattering will significantly influence the sound reduction by a noise barrier. A situation of interest with a large scale geometry is when using large buildings as road traffic noise barriers.

For predicting the effects of a turbulent atmosphere on sound reduction by a thin, hard screen, a model developed by Daigle [2] is used. In the model the energy scattered by the turbulence is calculated using the sound scattering cross-section by Tatarskii [4] and then added to the diffracted energy in the shadow of the screen. With this model Daigle investigated five different geometries and the predictions were compared with measured data [2]. The comparison showed a fairly good agreement between predictions and measurements, and that neglecting the turbulence scattering would yield a poor prediction, especially at higher frequencies.

To determine when the atmospheric turbulence significantly influences the sound reduction by a screen, a large set of situations need to be investigated, i.e. many parameters need to be varied. The model used does allow the results predicted for one situation to be straight forwardly transformed to other situations and thereby the number of parameters used in the calculations can be reduced. Using the physically based Kolmogorov spectrum for the representation of the turbulence allows a straight forward transformation of the results for one frequency to other frequencies. In this study no ground effects are taken into account, leading to a straight forward frequency dependence of the diffraction as well. Moreover, the results when enlarging or diminishing the geometry in scale can also be predicted using straight forward transformations, both for the scattering and the diffraction. Considering all these transformation properties of the model, the predictions of the scattering and the diffraction for all situations of interest can be compactly presented as a small amount of data, as shown in the following.

When omitting the ground surface in the predictions the barrier insertion loss will in general be overestimated. For instance, if the receiver is placed on a hard ground, the overestimation will be 6 dB (the scattered level relative to the diffracted field will, however, be the same). If the receiver is placed above the ground, the insertion loss will be more difficult to predict since it will be determined by the interference between direct and ground reflected waves. For high enough frequencies, however, the direct and ground reflected waves, from both diffraction and scattering, will add energy wise, since the waves will be uncorrelated due to the randomness of the medium as well as of the ground surface. Then, the insertion loss will be overestimated by about 3 dB for an elevated receiver, and the scattered level relative to the diffracted field will be the same as without ground.

For future work a model similar to the one used here can be developed to take into account a finite impedance ground surface, thick barriers of finite length, a non-constant sound speed profile, and locally homogeneous turbulence. Moreover, it should be possible to include the decorrelation between a direct and a ground reflected wave that is due to the atmospheric turbulence.

2. Theory

The acoustic energy scattered into the shadow of the screen is calculated using the sound scattering cross-section by Tatarskii [4]. The diffracted energy is calculated separately and then added to the scattered energy, according to the model developed by Daigle [2].

2.1 Diffraction

The diffraction is calculated for a thin, hard screen using uniform theory of diffraction [5, 6]. When no ground is present the diffracted energy is inversely proportional to the frequency. Analogously, if the geometry is increased in scale, by some scaling factor, the diffracted energy relative to free field is inversely proportional to the scaling factor.

The main restriction of the uniform theory of diffraction is that it is only applicable when the source and receiver are located more than a quarter of a wavelength away from the screen [7]. For a more extensive description of the uniform theory of diffraction, see e.g. [5].

2.2 Sound scattering cross-section

The sound scattering cross-section is a single scattering approximation where the field incident on a scattering object is assumed to be well approximated by the field calculated for a non-turbulent atmosphere. The energy scattered from each object will be added to the total field and thus the model is not energy conserving. This means that it is restricted to small perturbations of the sound field, which implicates that the propagation distance cannot be too large. Also the fluctuations of the medium have to be small, so that the acoustic field inside a scattering object can be approximated by the incident field, i.e. the Born approximation.

The atmospheric turbulence is approximated as homogeneous and isotropic, which means that it is described by the same statistics in all points and in all directions.

Furthermore a far field condition has to be fulfilled,

$$\rho >> l^2/\lambda \, , \tag{1}$$

where l is the correlation length of the turbulence (about 1 m), λ the acoustic wavelength, and ρ the distance from a scattering elementary volume to the receiver (see Figure 1). Condition (1) justifies an uncorrelated summation of the contribution from different elementary scattering volumes and the total received scattered energy can be written as [2]

$$E_S = \int_V p_0^2 \frac{\sigma(\theta)}{\rho^2} dV \,, \tag{2}$$

where p_0 is the amplitude of the incident pressure, $\sigma(\theta)$ the scattering cross-section, and θ the scattering angle. The volume of integration V consists of all points in line of sight from both source and receiver (i.e. the striped area in Figure 1).

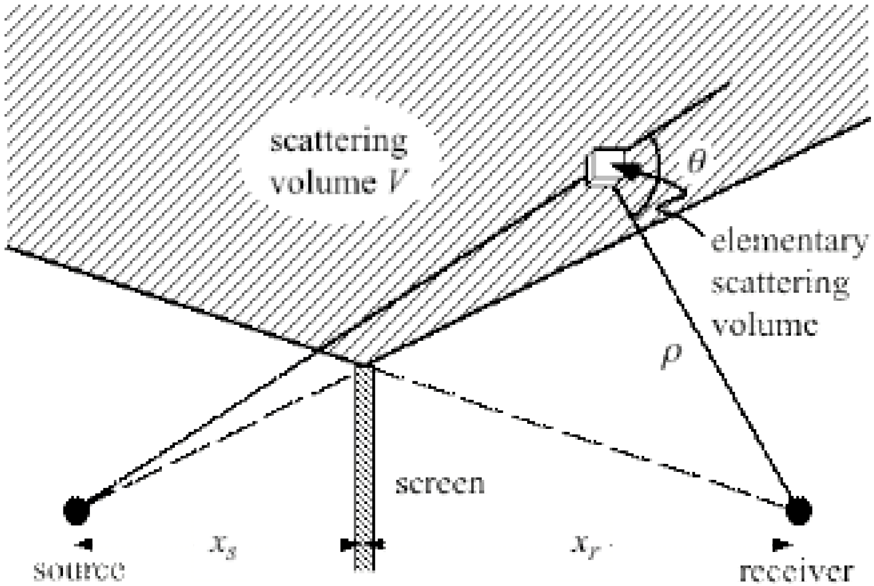

Figure 1. Geometry for the sound scattering cross-section.

Following Tatarskii [4, p. 160] the scattering cross-section is written

$$\sigma(\theta) = \frac{\pi k^4}{2} \cos^2 \theta \left[\frac{\Phi(\kappa)}{T_0^2} + \frac{4F(\kappa)}{c_0^2} \cos^2 \frac{\theta}{2} \right], \tag{3}$$

where $\Phi(\kappa)$ and $F(\kappa)$ are the spectral densities of the temperature and the wind velocity fluctuations respectively, T_0 the mean temperature, c_0 the mean sound velocity, and κ the wave number of the turbulence, fulfilling the Bragg condition

$$\kappa = 2k \sin \frac{\theta}{2} \,. \tag{4}$$

It can be noted in equation (3) that for right angles $\cos^2 \theta = 0$, and the scattering cross-section will be zero.

The incident pressure p_0 in equation (2) is calculated without taking into account the field diffracted by the screen. This will lead to an overestimation of the scattered energy since the strongest scattering will come from parts of the scattering volume that are near the shadow boundary, where the incident pressure is weakened by diffraction. A more accurate prediction of the scattered energy can be obtained by considering the diffracted field in the entire scattering volume.

Equation (2) describes the time average of the energy scattered by the turbulence. The turbulence can be seen as a composition of Bragg planes with separation distance 2□/□ causing scattering of energy proportional to the spectral density at | |.

According to this model the scattered energy will, relative to free field, change with the same factor as the geometry is scaled. To see this let the height of the screen, as well as its distance from source and receiver, be doubled. Substituting for these new variables in the integral (2) will cause an increase by a factor eight in dV and a factor four in □^{2}, whereas p_0^2 will stay constant relative to free field. As a result the scattered energy will be doubled, i.e. increased by 3 dB, relative to free field. This dependence of the scattered energy on the scaling of the geometry is, due to the single scattering approximation, restricted to short ranges, as stated above. It is, however, assumed here that, for frequencies of interest for road traffic noise situations, the single scattering approximation is realistic up to at least a few hundred meters in range. Measurements or further theoretical work is needed to confirm the validity of this assumption.

Both □(□) and F(□) in equation (3) are assumed to be described by the Kolmogorov spectrum (see Figure 2), with amplitudes C_T^2 and C_v^2 respectively.

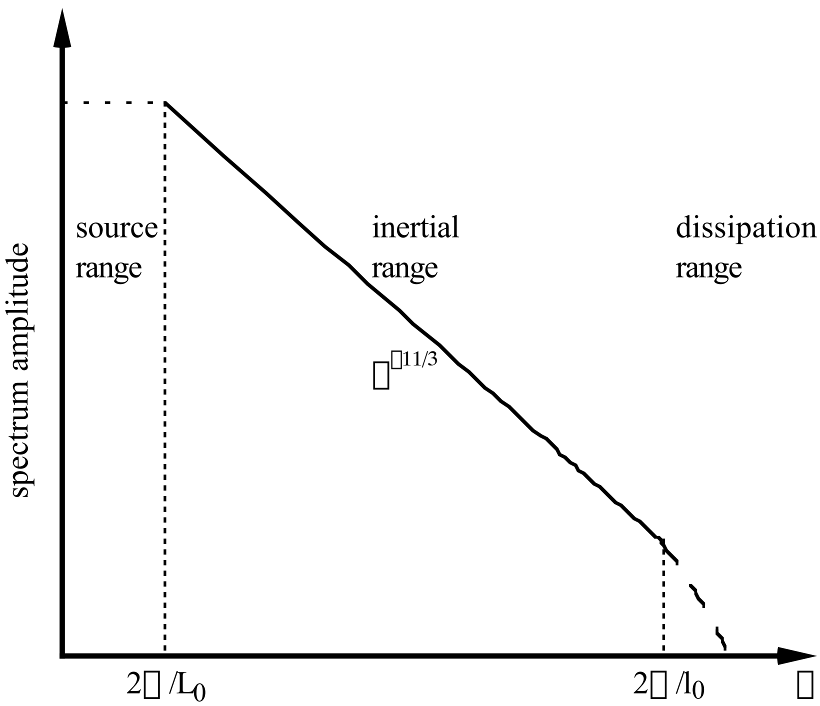

Figure 2. Kolmogorov spectrum of the turbulence.

In the inertial range, where the spectrum amplitude is proportional to $\kappa^{-11/3}$, the scattering cross-section can be written as

$$\sigma(\theta) = 0.38k^{1/3}\frac{\cos^2\theta}{\left(2\sin(\theta/2)\right)^{11/3}}\left[0.13\frac{C_T^2}{T_0^2}+\frac{C_v^2}{c_0^2}\cos^2\frac{\theta}{2}\right]. \tag{5}$$

In equation (5) it can be seen that the scattered energy changes with frequency as $f^{1/3}$.

The strength of the turbulence in the source range, i.e. for $\kappa < 2\pi/L_0$, will depend on the large structures of the terrain and is not easily determined. In this study the spectrum amplitude in the source range is assumed to be constant, at a value equal to the amplitude at $\kappa = 2\pi/L_0$ for the inertial range. When calculating the integral (2) the constant value of the spectrum in the source range has to be considered if the scattering angle theta is small or if the frequency is low, according to the Bragg condition (4). This leads to that only in the situations when a negligible part of the scattered energy comes from the source range can the straight forward frequency scaling according to equation (5) be applied.

The value of l_0 is as small as 1-2 mm and therefore the dissipation range will not be of importance in the audio range.

2.3 Implementation

When calculating the integral (2) numerically, the volume of integration V is increased until further contribution to the scattered energy is negligible. For flat geometries, i.e. when the source and receiver are located far away from a low screen, a sufficient volume of integration is from the source to the receiver about L high and $2L$ wide, where L is the distance between the source and receiver. However, for less flat geometries there will be significant back scattering, i.e. scattering at angles greater than 90°, and then the volume of integration has to be increased.

The integral (2) can be solved analytically in one dimension by taking advantage of the angle dependence of the integrand, as shown in Appendix 1. This makes the numerical solution far quicker.

3. Results

In the calculations the values of the parameters for the strength of the turbulence are chosen with guidance from Daigle's measurements [2] so as to represent a strong but not unrealistically strong turbulence: $C_v^2 = 1$, $C_T^2 = 10$, and $L_0 = 1.1$ m.

In the first subsection the general results are presented and in the second subsection the influence on a typical road traffic noise spectrum is calculated for one geometry.

3.1 General results

The results are presented in two sets of tables. The variables are the screen height H and the screen-receiver distance x_r, in meters. Each set of tables consists of one table with the diffracted level relative to free field L_{D0} and one table with the scattered level relative to the diffracted field ΔL_{S0}. The results are presented for the frequency $f_0 = 2000$ Hz, and for a distance $x_{s0} = 40$ m from the source to the screen. The first set of tables (Tables 1 and 2) describes the situation where the receiver is on the same height as the source (see Figure 3). The second set of tables (Tables 3 and 4) describes the situation where the receiver is half the screen height above the source (see Figure 4).

The results can be transformed for another value of the frequency f or of the source-screen distance x_s. If x_s is changed, the tabulated results at the screen height $H \cdot x_{s0} / x_s$ and at the screen-receiver distance $x_r \cdot x_{s0} / x_s$ should be used. Then, to the results for the scattering $10 \cdot \log(x_s / x_{s0})$ is added, and to the results for the diffraction $10 \cdot \log(x_s / x_{s0})$ is subtracted. For a change in frequency $10/3 \cdot \log(f / f_0)$ is added to the scattered level and $10 \cdot \log(f / f_0)$ is subtracted from the diffracted level. Hence, the scattered level relative to the diffracted field will increase by 6 dB if the geometry is enlarged in scale by a factor two. For a doubling of frequency the increase will be 4 dB. The resulting levels using the above transformations can also be formulated as

$$\Delta L_S = \Delta L_{S0} + 10 \cdot \log(x_s / x_{s0}) + 10/3 \cdot \log(f / f_0) \tag{6}$$

and

$$L_D = L_{D0} - 10 \cdot \log(x_s / x_{s0}) - 10 \cdot \log(f / f_0) \ , \tag{7}$$

where ΔL_S is the scattered level relative to the diffracted field and L_D the diffracted level relative to free field. The total level L_{D+S} can then be written

$$L_{D+S} = 10 \cdot \log\left(10^{L_D/10} + 10^{(L_D + \Delta L_S)/10}\right) . \tag{8}$$

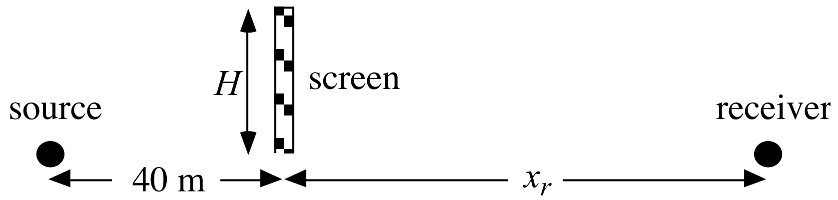

Figure 3. Geometry with the receiver at the same height as the source.

	x_r=10	20	30	40	50	60	70	80	90	100
H=5	-26.4	-25.0	-24.2	-23.7	-23.3	-23.0	-22.8	-22.6	-22.5	-22.4
10	-31.1	-30.0	-29.3	-28.9	-28.6	-28.3	-28.1	-28.0	-27.9	-27.8
15	-33.9	-32.9	-32.3	-31.8	-31.5	-31.3	-31.1	-31.0	-30.8	-30.7
20	-36.1	-35.1	-34.4	-33.9	-33.6	-33.4	-33.2	-33.0	-32.9	-32.8
25	-38.0	-36.9	-36.1	-35.6	-35.3	-35.0	-34.8	-34.6	-34.5	-34.3
30	-39.6	-38.5	-37.6	-37.1	-36.7	-36.4	-36.1	-35.9	-35.8	-35.6
35	-41.1	-39.9	-39.0	-38.4	-37.9	-37.6	-37.3	-37.1	-36.9	-36.7
40	-42.5	-41.2	-40.2	-39.5	-39.0	-38.6	-38.3	-38.1	-37.9	-37.7

Table 1. Diffracted level relative to free field, L_{D0} (dB), at the same height as the source.

	x_r=10	20	30	40	50	60	70	80	90	100
H=5	-7.1	-3.0	-0.6	1.0	2.2	3.1	3.9	4.5	5.1	5.6
10	-6.3	-4.4	-2.5	-0.9	0.4	1.4	2.3	3.0	3.7	4.2
15	-5.0	-3.8	-2.6	-1.5	-0.5	0.4	1.2	1.9	2.6	3.1
20	-4.1	-2.9	-2.0	-1.1	-0.4	0.3	1.0	1.6	2.1	2.6
25	-3.4	-2.1	-1.2	-0.5	0.1	0.7	1.3	1.8	2.3	2.7
30	-2.9	-1.6	-0.6	0.1	0.7	1.3	1.8	2.2	2.7	3.1
35	-2.5	-1.2	-0.2	0.6	1.2	1.8	2.3	2.7	3.1	3.5
40	-2.2	-0.8	0.2	1.0	1.7	2.2	2.7	3.1	3.5	3.9

Table 2. Scattered level relative to the diffracted field, ΔL_{S0} (dB), at the same height as the source.

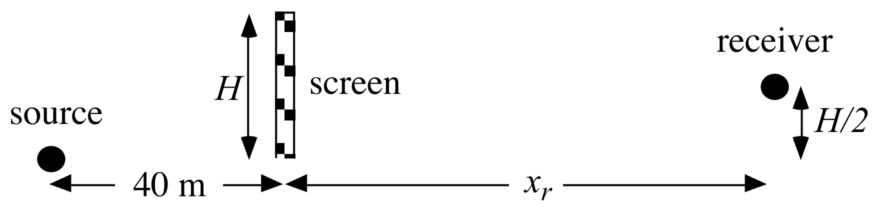

Figure 4. Geometry with the receiver half the screen height above the source.

	x_r=10	20	30	40	50	60	70	80	90	100
H=5	-22.7	-21.9	-21.6	-21.4	-21.3	-21.2	-21.2	-21.2	-21.2	-21.1
10	-27.7	-27.1	-26.9	-26.7	-26.7	-26.6	-26.6	-26.6	-26.6	-26.6
15	-30.5	-30.0	-29.8	-29.7	-29.6	-29.6	-29.6	-29.6	-29.6	-29.6
20	-32.5	-32.1	-31.9	-31.8	-31.7	-31.7	-31.6	-31.6	-31.6	-31.6
25	-34.2	-33.7	-33.5	-33.3	-33.3	-33.2	-33.2	-33.2	-33.1	-33.1
30	-35.6	-35.1	-34.8	-34.6	-34.5	-34.5	-34.4	-34.4	-34.4	-34.4
35	-36.9	-36.3	-35.9	-35.7	-35.6	-35.6	-35.5	-35.5	-35.4	-35.4
40	-38.0	-37.3	-37.0	-36.7	-36.6	-36.5	-36.4	-36.4	-36.3	-36.3

Table 3. Diffracted level relative to free field, L_{D0} (dB), at half the screen height above the source.

	x_r=10	20	30	40	50	60	70	80	90	100
H=5	-6.0	-2.0	0.1	1.5	2.6	3.4	4.1	4.7	5.3	5.7
10	-7.3	-3.8	-1.6	-0.0	1.2	2.1	2.9	3.6	4.1	4.7
15	-6.6	-4.5	-2.6	-1.1	0.0	1.0	1.8	2.5	3.1	3.6
20	-5.7	-4.1	-2.7	-1.5	-0.4	0.4	1.2	1.8	2.4	2.9
25	-4.9	-3.4	-2.3	-1.3	-0.4	0.4	1.1	1.7	2.2	2.7
30	-4.3	-2.8	-1.7	-0.8	-0.0	0.7	1.3	1.9	2.4	2.8
35	-3.8	-2.3	-1.2	-0.3	0.4	1.1	1.6	2.2	2.7	3.1
40	-3.4	-1.9	-0.8	0.1	0.8	1.5	2.0	2.5	3.0	3.4

Table 4. Scattered level relative to the diffracted field, ΔL_{S0} (dB), at half the screen height above the source.

From the tabulated results it can be seen that the influence of the scattering grows when the distance from the screen to the receiver x_r is increased. When the screen height H is increased, it can be seen that the influence of the scattering first decreases and then increases, which is due to the weak scattering near 90°. Hence, when the screen height is large, the dominating scattering is at angles larger than 90°. When the screen height is further increased, also the influence of the scattering will increase. This dependence would be different for other spectral densities of the turbulence. For instance, a Gaussian spectral density would lead to a faster decrease of the scattered energy relative to free field when the height of a high screen is further increased.

As already discussed above, the transformation of the scattered level when changing the frequency is only valid within the inertial range of the turbulence spectrum. To get a rough estimate of when this transformation is valid one can use the Bragg condition (4) for the smallest scattering angle (i.e. at the screen edge) and thereby find a lower frequency limit. For example, if the receiver is half the screen height above the source (see Figure 4) and if $H = 10$ m and $x_r = 100$ m, the smallest scattering angle is about 17°. Inserting $\theta = 17°$, $\kappa = 2\pi/L_0$, and $k = 2\pi f/c$ in the Bragg condition (4) leads to a lower frequency limit $f = c/(2L_0 \sin\frac{\theta}{2}) \approx 1050$ Hz, with $c = 340$ m/s. For even lower frequencies the scattering will be overestimated using this prediction scheme. For many situations, however, the dominating scattering will be produced at higher frequencies, and the contribution at low frequencies can be omitted.

3.2 Influence on road traffic noise

The geometry in the example above, with $H = 10$ m, $x_r = 100$ m, $x_s = 40$ m, and with the receiver half the screen height above the source, can be seen as a model for a building along the road side (see Figure 4). The tabulated results, for this geometry and the frequency $f_0 = 2000$ Hz, are $L_{D0} = -26.6$ dB and $\Delta L_{S0} = 4.7$ dB. By applying the formulas (6-8) for transformation of the results to other frequencies, the influence on a traffic noise spectrum can be estimated for the geometry. For this example a reference traffic noise spectrum according to ISO 717-1:1886(E) is used (see Figure 5). The spectrum is for a car speed of 90 km/h and has been normalised to 0 dB(A). Not to overestimate the scattering at low frequencies, the scattered energy is assumed to be zero up to the third octave band 800 Hz.

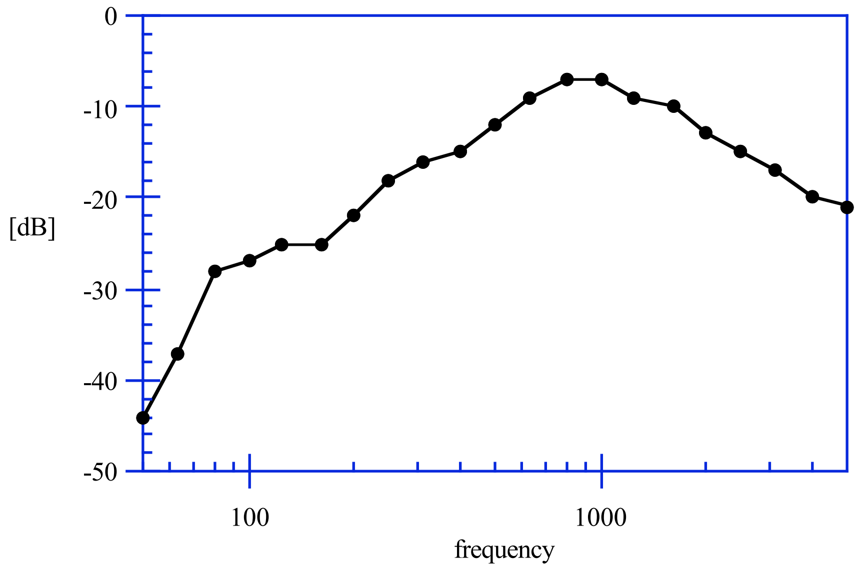

Figure 5. A-weighted reference traffic noise spectrum in third octave bands, normalised to 0 dB(A).

The resulting spectra for the diffraction L_D and for the total level, including the scattering by the turbulence, L_{D+S} are shown in Figure 6. The diffracted level is about -22 dB(A), and it can also be seen that the screen causes an increased influence of the low frequency components of the traffic noise. (It can be noted again that, for a hard ground surface directly beneath the receiver, the sound reduction by the barrier would decrease by 6 dB, i.e. from -22 dB(A) to -16 dB(A).) The difference between the total level L_{D+S} and the diffracted level L_D show, at the frequencies above 800 Hz, a decrease in insertion loss of about 5-7 dB due to the scattering by turbulence. The resulting A-weighted contribution by turbulence scattering is about 2.5 dB for the situation. This will be even increased taking into account the scattered energy in the third octave bands at 800 Hz and below. In order to compensate for the decreased sound reduction due to turbulence scattering, the screen height must be increased by almost 5 m (see Tables 3 and 4).

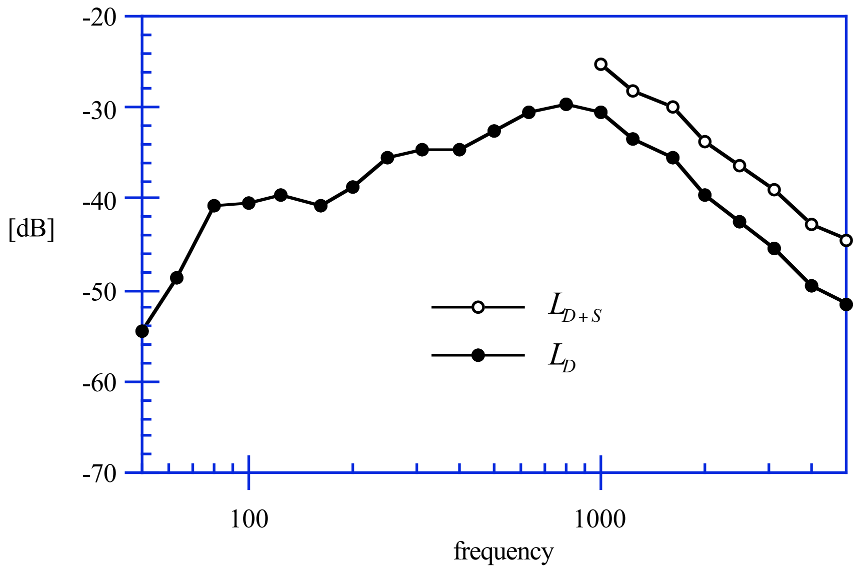

Figure 6. Contribution by turbulence scattering on screened traffic noise.

Conclusions

The presented prediction scheme uses a small number of pre-calculated data to efficiently predict the turbulence scattering and the diffraction for a large variety of situations. This is done by applying transformations for variations in frequency and in geometrical scale, for both the scattered and the diffracted energies.

The influence of the turbulence scattering on the sound reduction by a thin, hard screen grows when the geometry is increased in scale or when the frequency is increased. The results when changing the screen height or the screen-receiver distance show a more complex pattern. What can be concluded is that the influence of the scattering grows when the screen-receiver distance is increased, and that the weak scattering at angles near 90° leads to a dip in the influence of the scattering when the screen height is increased. Moreover, the influence of the turbulence scattering can be strong for both high and low screens. However, measurements have to be carried out for a large variety of situations in order to verify the model and determine its limitations in applicability. Moreover, more measurements of the strength of the turbulence are needed in order to ensure that values appropriate for the situations are used in the predictions.

The calculated example for one geometry and with a traffic noise spectrum as input shows that taking onto account atmospheric turbulence can significantly reduce the performance of a noise barrier, not only at high frequencies, but also when measured in dB(A).

For future work a model similar to the one used here can be developed to take into account a finite impedance ground surface, thick barriers of finite length, a non-constant sound speed profile, and locally homogeneous turbulence. Including the decorrelation, due to the atmospheric turbulence, between a direct and a ground reflected wave should also be possible.

Acknowledgement

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Appendix 1

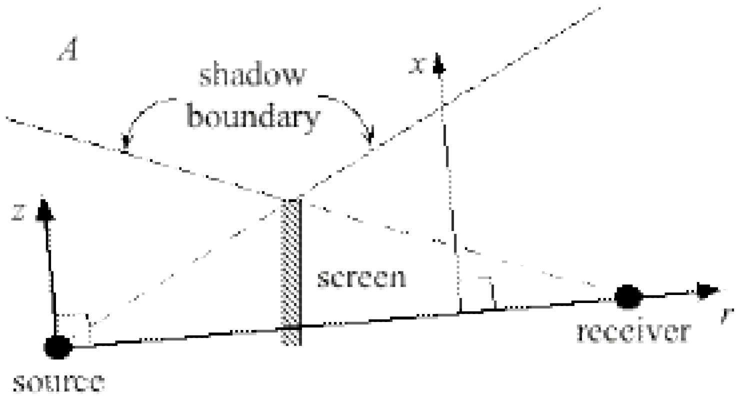

Figure A1.

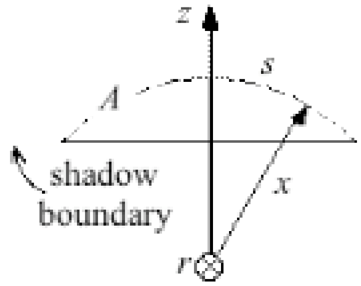

Figure A2.

Figures A1 and A2 show the geometry for the scattering cross-section calculations (see also Figure 1). The r axis passes through both the source and receiver (in Figure A2 the r axis is pointing down into the paper). Along the circle arc (dashed curve in Figure A2), drawn by the radius vector x, the scattering angle $\square$ is constant as well as the distance to the source and receiver. Therefore the integration along the arc is simply a multiplication by the arc length s which is determined by the length of the radius vector x and by the limiting height, i.e. the shadow boundary. Hence the volume integral in equation (2) can be rewritten as an area integral over the surface A above the shadow boundary,

$$\int_V p_0^2 \frac{\square(\square)}{\square^2} dV = \int_A p_0^2 \frac{\square(\square)}{\square^2} s\, dA \ , \qquad \text{(A1)}$$

where now all variables depend only on r and z.

If a ground surface is introduced, the calculation of the ground reflected scattered energy can be performed in a similar way. Then x will be perpendicular to the r axis through the mirror image point of the elevated receiver (or of the source if the source is elevated).