PROPAGATION OF ROAD TRAFFIC NOISE OVER GROUND OF MIXED TYPE

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1. INTRODUCTION

The effect of ground type on the propagation of sound has long been of interest; many authors have investigated propagation over homogeneous ground. More recently propagation over inhomogeneous ground has been considered and several approximate methods for the calculation of the propagation of sound from a harmonic point source over a two-impedance plane have been proposed [1-4].

One such method is described in this paper, a generalisation of the "compensation approach" method of Durnin and Bertoni [3]. This method is based on the boundary integral equation (BIE) method, which the authors have already discussed [5,6], and can be seen as an approximate form of the BIE method. The theory of the method in two and three dimensions is described and comparison made in two-dimensions with exact BIE calculations, and in three dimensions with the results of model experiments.

The application of the method to investigate traffic noise propagation over ground of mixed type is discussed.

2. THEORY

We are concerned with the propagation of sound from a harmonic point or line source over flat normally reacting ground of variable admittance. We assume a homogeneous medium in which the wave number is k. Let $\underset{\sim}{r}$, $\underset{\sim}{r}_o$ denote the receiver and source positions relative to some fixed point and $G_M(\underset{\sim}{r},\underset{\sim}{r}_o)$ the acoustic potential at $\underset{\sim}{r}$. $G_M(\underset{\sim}{r},\underset{\sim}{r}_o)$ satisfies a boundary value problem consisting of a homogeneous Helmholtz equation for $\underset{\sim}{r}\neq\underset{\sim}{r}_o$ in the region D above the ground, together with a normally reacting boundary condition at the ground surface ∂D, and a Sommerfeld radiation condition at infinity. It can be shown [5] that this boundary value problem is equivalent to the integral equation, for $\underset{\sim}{r}$ in D and ∂D,

$$G_M(\underset{\sim}{r},\underset{\sim}{r}_o)=G_{\beta c}(\underset{\sim}{r},\underset{\sim}{r}_o)-ik\int_{\partial D} G_{\beta c}(\underset{\sim}{r},\underset{\sim}{r}_s)G_M(\underset{\sim}{r}_s,\underset{\sim}{r}_o)(\beta(\underset{\sim}{r}_s)-\beta_c)\,dS(\underset{\sim}{r}_s) \quad (1)$$

In this equation $\beta(\underset{\sim}{r}_s)$ is the admittance at a point $\underset{\sim}{r}_s$ in the ground surface and β_c is an (arbitrary) constant value of admittance; $G_{\beta c}(\underset{\sim}{r},\underset{\sim}{r}_o)$ is the potential that would be observed at $\underset{\sim}{r}$ if the ground had constant admittance β_c. Equation (1) holds both in three dimensions with a point source, and for effectively two-dimensional problems when the source is a line source and $\beta(\underset{\sim}{r}_s)$ is constant in a direction parallel to it. The integral over ∂D is a surface or line integral in these two cases respectively. Figure 1 shows the two-dimensional case, the plane of the paper being perpendicular to the line source and $\beta(\underset{\sim}{r}_s)$ a function of x alone (independent of y). We have also assumed that $\beta(\underset{\sim}{r}_s) = \beta_c$ outside a region ∂D_1 of ∂D. When this is the case ∂D in (1) may be replaced by ∂D_1.

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The numerical solution of (1) has been discussed previously [5,6]. A set of linear equations is solved to determine values of $G_M(\underset{\sim}{r},\underset{\sim}{r}_o)$ for $\underset{\sim}{r}$ in ∂D_1. Subsequently these values are substituted in the right hand side of equation (1) to calculate by numerical integration $G_M(\underset{\sim}{r},\underset{\sim}{r}_o)$ at any point in D. For either of these steps to be possible we must be able to calculate accurately $G_{\beta c}(\underset{\sim}{r},\underset{\sim}{r}_o)$, the solution for uniform surface admittance. This has been discussed in the appendix of [5].

A particularly simple case of considerable interest is when ∂D_1 is a half-plane, the source lies above ∂D_1, and $\beta(\underset{\sim}{r}_s) \equiv \beta$, a constant, for $\underset{\sim}{r}_s$ in ∂D_1. With those restrictions equation (1) describes propagation above a plane consisting of two impedance half-planes. In this case we may adopt on intuitive physical grounds the approximation $G_M(\underset{\sim}{r},\underset{\sim}{r}_o) \approx G_\beta(\underset{\sim}{r},\underset{\sim}{r}_o)$ for $\underset{\sim}{r}$ in ∂D_1, whereupon equation (1) becomes,

$$G_M(\underset{\sim}{r},\underset{\sim}{r}_o) = G_{\beta c}(\underset{\sim}{r},\underset{\sim}{r}_o) - ik(\beta-\beta_c) \int_{\partial D_1} G_{\beta c}(\underset{\sim}{r},\underset{\sim}{r}_s) G_\beta(\underset{\sim}{r}_s,\underset{\sim}{r}_o) dS(\underset{\sim}{r}_s) \qquad (2)$$

While this approximation is not as accurate as the correct numerical solution, which can be made as accurate as desired with sufficient computing power, it is computationally preferable as the expensive exact solution of (1), for $G_M(\underset{\sim}{r}_s,\underset{\sim}{r}_o)$, $\underset{\sim}{r}_s$ in ∂D_1 has been avoided. The approximate equation (2) is a generalisation of the 'compensation approach' approximation of Durnin and Bertoni [3], who consider only the case where source and receiver are in the ground surface and either β_c or β is zero.

In the two-dimensional case, illustrated in figure 1 if we take $a \to -\infty$ and $\beta(x) \equiv \beta$ constant, equation (2) is explicitly;

$$G_M(\underset{\sim}{r},\underset{\sim}{r}_o) = G_{\beta c}(\underset{\sim}{r},\underset{\sim}{r}_o) + \frac{ik}{16} (\beta-\beta_c) \int_{-\infty}^{b} H_o^{(1)}(kR_1)(1+Q^{(2)}(\beta,z_o,x)) \cdot H_o^{(1)}(kR_2)(1+Q^{(2)}(\beta_c,z,r-x))\,dx \qquad (3)$$

Here we have written $G_\beta(\underset{\sim}{r}_s,\underset{\sim}{r}_o) = -\frac{i}{4} H_o^{(1)}(kR_1)(1+Q^{(2)}(\beta z_o,x))$, and similarly $G_{\beta c}(\underset{\sim}{r},\underset{\sim}{r}_s) = -\frac{i}{4} H_o^{(1)}(kR_2)(1+Q^{(2)}(\beta_c,z,r-x))$; that is $Q^{(2)}(\beta,Z,X)$ is a cylindrical wave reflection coefficient at homogeneous ground of admittance β, with Z the sum of source and receiver heights and X the horizontal separation of source and receiver. $H_o^{(1)}$ is the Hankel function of the first kind of order zero and $R_1 = \sqrt{(x^2+z_o^2)}$, $R_2 = \sqrt{((r-x)^2+z^2)}$. Calculations have been made, comparing $G_M(\underset{\sim}{r},\underset{\sim}{r}_o)$ calculated by numerical integration of (3) with the value calculated by exact solution of equation (1). Calculations were made for the case in which one half-plane is rigid (β_c=0) and the other half-plane has admittance β given by equation (7) with flow resistance σ = 250000Nsm^{-4}. This equation and value of σ have been commonly used to model the admittance of grassland. Calculations were made with z_o=z=1.0m, r=1,5,10,20...,50m, b=0,5,...,20m and for each 1/3 octave centre frequency f in the range 100≤f≤2000 Hz. A maximum deviation of 0.13 dB was noted between the approximate and the exact solution.

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In the corresponding three-dimensional case of propagation from a point source over a two-impedance plane with the line of discontinuity of impedance perpendicular to the line from source to receiver, equation (2) is explicitly

$$G_M(\underset{\sim}{r},\underset{\sim}{r}_o)=G_{\beta c}(\underset{\sim}{r},\underset{\sim}{r}_o) - \frac{ik}{16\pi^2}(\beta-\beta_c)\int_{-\infty}^{b} dx \int_{-\infty}^{+\infty} \frac{e^{ik(R_A+R_B)}}{R_A R_B}(1+Q^{(3)}(\beta,z_o r_A))(1+Q^{(3)}(\beta_c,z,r_B))dy \qquad (4)$$

where $Q^{(3)}(\beta,Z,X)$ is a spherical wave reflection coefficient (β,Z,X defined as in $Q^{(2)}(\beta,Z,X)$) and

$$R_A=\sqrt{R_1^2+y^2},\ R_B=\sqrt{R_2^2+y^2},\ r_A=\sqrt{x^2+y^2},\ r_B=\sqrt{(r-x)^2+y^2}$$

It can be shown [5] that the approximations for $G_M(\underset{\sim}{r},\underset{\sim}{r}_o)$ of equations (3) and (4) satisfy reciprocity. The integration with respect to y in equation (4) may be performed approximately by the method of stationary phase, giving,

$$G_M(\underset{\sim}{r},\underset{\sim}{r}_o)=G_{\beta c}(\underset{\sim}{r},\underset{\sim}{r}_o)+\frac{k}{16\pi}\sqrt{\frac{\pi k}{2}}\,e^{i\pi/4}(\beta-\beta_c)\int_{-\infty}^{b}(R_1+R_2)^{-\frac{1}{2}}H_o^{(1)}(kR_1)(1+Q^{(3)}(\beta,z_o,x))\cdot H_o^{(1)}(kR_2)(1+Q^{(3)}(\beta_c,z,r-x))dx \qquad (5)$$

Using equation (5) the potential may be calculated as rapidly in the three-dimensional as in the two-dimensional case.

3. COMPARISON WITH EXPERIMENTAL RESULTS

Propagation over a two impedance plane has been investigated by experiment in an anechoic chamber. The source was the open end of a stout brass tube of internal diameter 4.5mm, the other end of which was connected to a speaker mounted inside an insulated box. The receiver was a ½" microphone. The two surfaces were a hard surface of melamine-covered chipboard, and a soft surface produced by covering this with a 10mm thick foam backed carpet. The heights of source and receiver above the hard surface were 85 and 63mm, respectively, and their horizontal separation was 1.0m. Narrow band (50Hz) spectra between 1 and 20 kHz were measured for propagation over hard, soft, and mixed surfaces with a quarter, half, and three-quarters of the surface soft. In all cases the boundary was perpendicular to the direction from source to receiver with the soft ground below the receiver. The free-field spectrum was also measured to enable the excess attenuation spectrum to be calculated for propagation over each surface type.

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Theoretical curves for the experimental conditions are shown in figure 2. Excess attenuation, defined by,

$$EA = -20 \log_{10} \left| G_M(\underset{\sim}{r},\underset{\sim}{r}_o)/G(\underset{\sim}{r},\underset{\sim}{r}_o) \right| , \qquad (6)$$

where G_M,G are the total potential and the potential of the direct wave, respectively, is plotted against frequency. The curves are calculated by numerical integration of equation (5) in the two-impedance ground cases. The hard ground was assumed perfectly rigid, and the soft ground assumed homogeneous with admittance β_G, given by,

$$1/\beta_G = 1+9.08(1000f/\sigma)^{-0.75} + i11.9(1000f/\sigma)^{-0.73} \qquad (7)$$

where f and σ are frequency and flow resistance respectively in SI units.

This equation, due to Delany and Bazley [7], has been used successfully to model the admittance of grassland [8]. Assuming further that the soft ground is normally reacting, has thickness T, and complex wave number k_G satisfying Delany and Bazley's equation [7],

$$k_G = k(1+10.8(1000f/\sigma)^{-0.70} + i\ 10.3(1000f/\sigma)^{-0.59}), \qquad (8)$$

the normal surface admittance is [9],

$$\beta = -\tan(Tk_G)\beta_G \qquad (9)$$

This equation is used in calculating figure 2, with T=10mm, the experimental value, and σ chosen as 300 000 Nsm^{-4} to give the best fit to the experimental results.

Examining figure 2 we see that as the proportion of soft ground increases the interference minimum in the EA spectrum associated with geometrical reflection effects disappears, and a minimum of lower frequency characteristic of soft ground reflection appears. An interesting point is that at low frequencies the curves for mixed ground converge to a level between and distinct from the levels for homogeneous soft and hard ground. This suggests that the ground type in the proximity of source or receiver is particularly important in determining EA level, a point which is discussed further in section 4.

The experimental and theoretical results are compared in figure 3, in which the experimental values have been averaged over 1/12th octave intervals. While the agreement is generally good, there is a certain amount of scatter particularly at low frequencies where few points are included in each 1/12th octave interval. This scatter is thought to be associated with imperfect absorption and background noise in the anechoic chamber; the similarity in pattern at low frequencies in each figure due to the same free-field spectrum being subtracted in each case. There are also systematic errors at the higher frequencies in the mixed ground cases, thought to be due to the 10mm step, between the hard and soft ground in the experiment, having been neglected in calculating the theoretical curves.

4. APPLICATION TO ROAD TRAFFIC NOISE

The method of section 2 has an obvious application to the calculation of the propagation of road traffic noise over mixed terrain. Using experimentally derived free-field vehicle frequency spectra and equation (5), the SPL due to a single vehicle, represented by an omni-directional point source, can be calculated as a function, SPL(R), of horizontal distance, R, for given receiver height. For an infinite straight traffic stream, consisting of a single vehicle type, the L_{eq} can be shown to be,

$$L_{eq} = 10 \log_{10} \{2D \int_0^{\infty} 10^{SPL(\sqrt{(y^2+r^2)})/10} dy \} \qquad (10)$$

where r is the horizontal distance of the receiver from the traffic stream and D is the traffic density (vehicles per unit length of road).

In deriving this equation in the two-impedance half-plane case, the dependence of SPL on the angle between the impedance boundary and the source-receiver direction is nglected; the angle is assumed to be 90°.

Examples of the use of this method are shown in figure 4. On comparing the curves it can be seen that the introduction of a small proportion of soft ground below the propagation path adjacent to the receiver produces a significant reduction in level at grazing incidence.

5 CONCLUSION

An approximate method for the calculation of the propagation of sound from a harmonic source over a two-impedance plane has been presented. This method is based on the boundary integral equation method and calculations comparing the two methods have shown agreement within 0.13dB in the two-dimensional case. The corresponding three-dimensional equation (5) for the case when the impedance discontinuity is perpendicular to the direction from source to receiver has been compared with experiment showing generally good agreement.

The computational time involved in evaluating the integral in equation (5) numerically is large when kb is large, but the use of the equation for the calculation of road traffic noise is feasible with a large main frame computer.

The application of equation (5) to the calculation of L_{eq} values has been briefly presented, and illustrated with two contour maps which suggest that even a small proportion of soft ground in the propagation path is significant at grazing incidence. Further work is in progress to investigate the effect of a variety of ground conditions.

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FIGURES

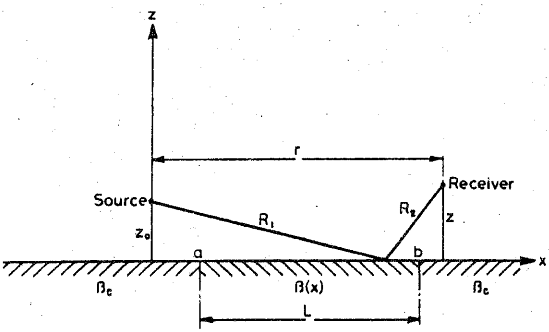

Figure 1. Geometry of source and receiver above an inhomogeneous plane.

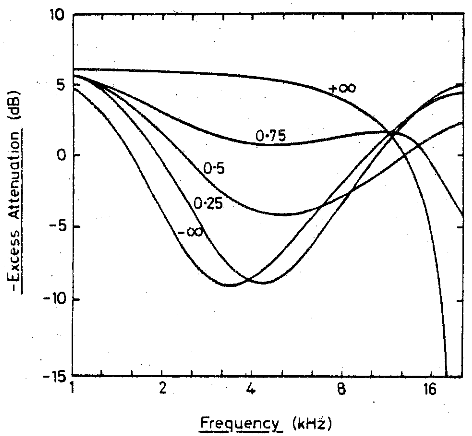

Figure 2. Theoretical excess attenuation of a spherical wave over homogeneous and inhomogeneous ground. Situation is figure 1 with $a=-\infty$, $r=1.0$m, $z_o=85$mm, $z=53$mm, $\beta(x)\equiv 0$, and β_c given by equation (7)-(9) with $T=10$mm, $\sigma=300\ 000$ Nsm^{-4}. Parameter is b in metres.

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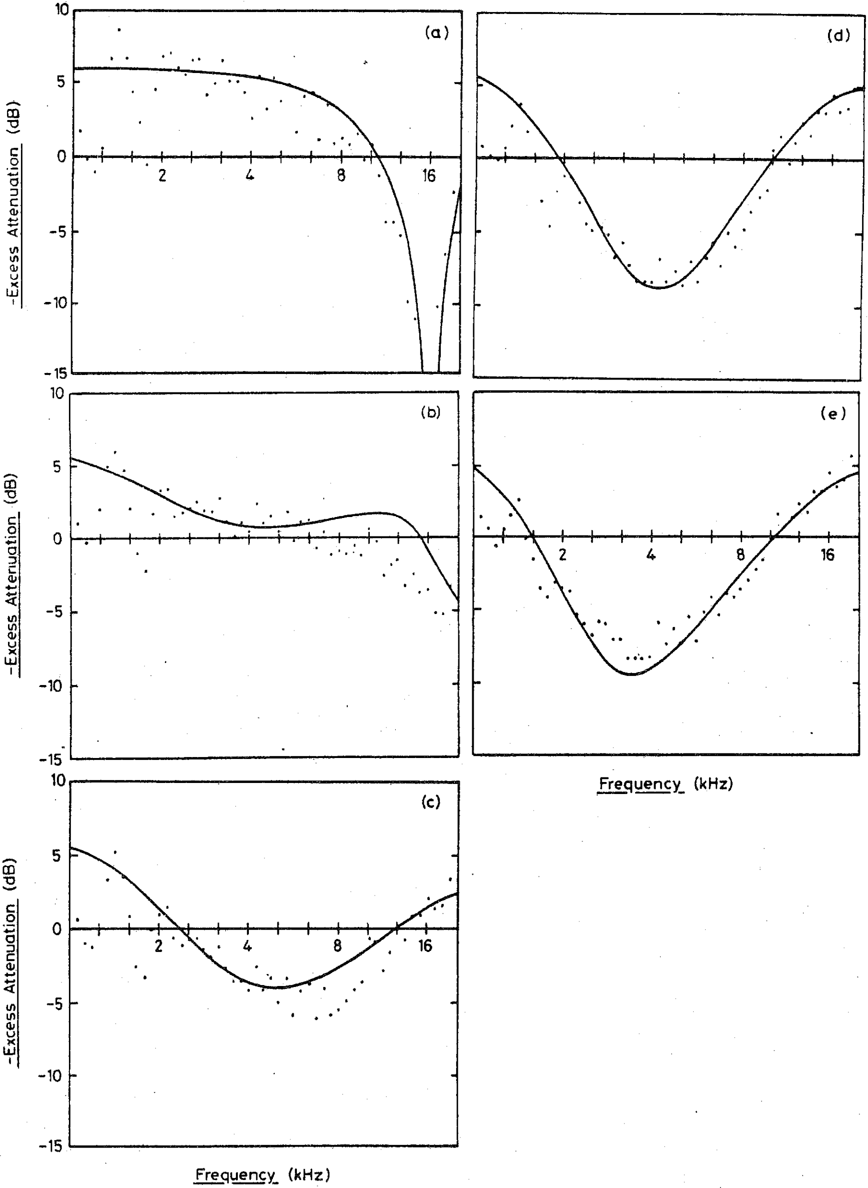

Figure 3. Excess attenuation of a spherical wave over homogeneous and inhomogeneous surfaces. As figure 1 with a=-∞, r=1.0m, z_o=85mm (75mm(e)), z=53mm (63mm(a)), β(x)≡0, and β_c calculated as in figure 2.—theoretical; •experimental. (a) b=+∞ (rigid surface); (b) b=0.75m; (c) b=0.5m; (d) b=0.25m; (e) b=- ∞(soft surface).

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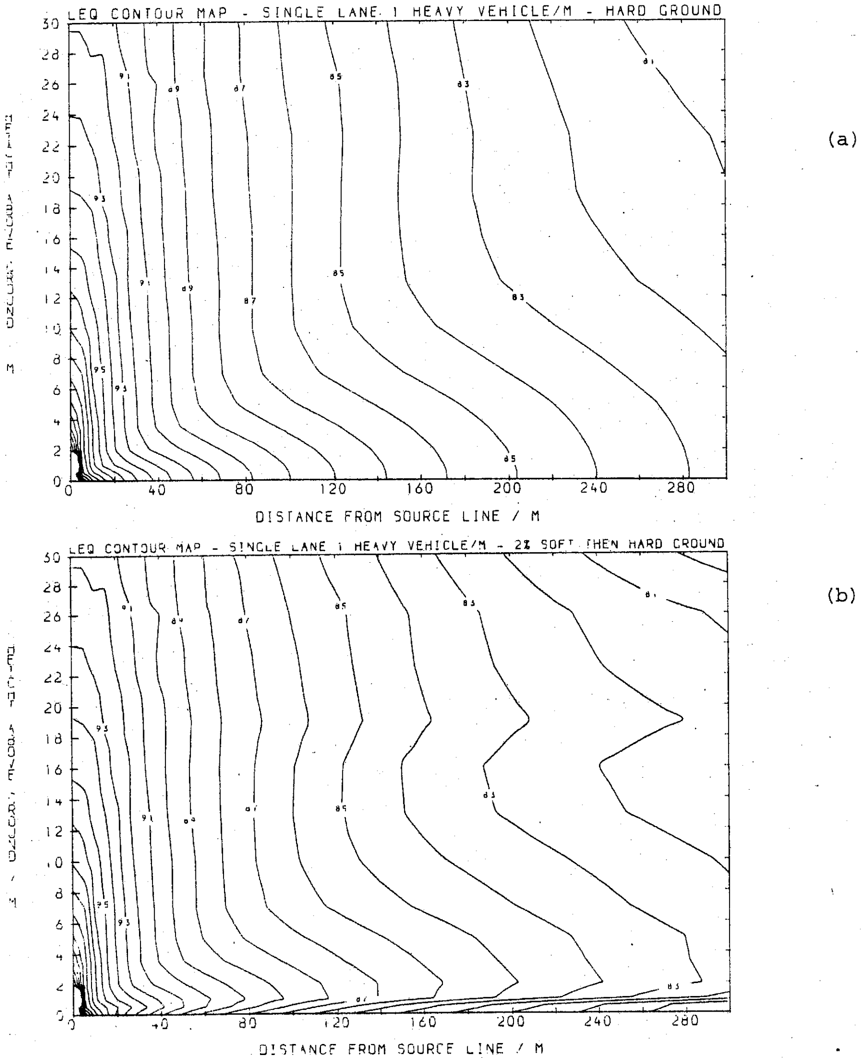

Figure 4. L_{eq} contour maps for propagation of traffic noise over level terrain. (a) hard ground, (b) half hard ground, half grassland with dividing line parallel to the road, and the grassland under the receiver and under the last 2% of the propagation path.