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ON THE LEAKAGE OF NOISE DUE TO THE PRESENCE OF HORIZONTAL AND VERTICAL GAPS IN BARRIERS

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ABSTRACT
Barriers are commonly used to reduce traffic noise. The construction cost and its performance are two major factors for consideration in the design stage. Sealing horizontal gaps between the noise barrier and the ground is normally required to ensure an 'air-tight' condition. This has a significant cost implication because a possible elimination of this procedure will save time and construction cost. On the other hands, vertical gaps are inevitable in some cases as they are required, for example, in the installation of a lamppost between two sections of a barrier. However, any noise leakage due to the vertical and horizontal gaps will lead to the degradation of the acoustic performance of the barrier. The purpose of this work is to investigate the effect of gaps in barriers. In the present study, a numerical model is developed to predict noise levels behind thin barriers of various gap sizes. As opposed to many computationally intensive schemes based on the Boundary Integral Method, the proposed numerical methodology enables one not only to study a two-dimensional model but also to investigate the sound fields behind a finite length barrier. In addition, indoor experiments have been conducted to validate the theoretical predictions.

1 - INTRODUCTION

Extensive research has been carried out to study the use of outdoor barriers as an effective measure for noise abatement. Most studies, which are based on a 2-dimensional model, focus on infinitely long barriers. However, relatively few studies have been concerned with the prediction of the acoustic performance of a finite length barrier. Notable exceptions are the use of the boundary integral equation method [1] and a line integral approach [2,3] to compute the sound fields. Lam [4], who has extended Maekawa's [5] semi-empirical method, has developed a simple numerical scheme that leads to a fairly accurate prediction of sound fields behind a barrier of finite length. There is a current interest in the investigation of the leakage effect due to gaps in barrier. In a recent study, Watts [6] has studied the 'leakage' of noise from a semi-infinite barrier both experimentally and theoretically. He used the Boundary Element Method to predict the leakage effect and compare it with his experimental data. He has also developed an empirical model for predicting noise levels that takes the leakage effect into consideration. In this paper, we develop a numerical model for the prediction of the noise leakage due to a finite size barrier. The numerical scheme is based on the theory developed by Thomasson [7] and Rasmussen [8]. To validate the proposed scheme, numerical predictions are compared with accurate indoor measurements.

2 - THEORY

The problem considered (Figure 1) consists of a two-dimensional flat locally reacting surface of infinite extent. A thin rigid screen of arbitrary shape, Γ_{B}, is situated at the plane of x=0. A point source with harmonic time dependency, $e^{-i\omega t}$, is located at $\mathbf{r}_S \equiv (x_S, y_S, z_S)$ where x_S<0. We wish to investigate the sound field behind the rigid screen where the receiver is located at $\mathbf{r}_R \equiv (x_R, y_R, z_R)$ where x_R>0. Thomasson [7] and Rasmussen [8] studied sound diffraction by a thin screen above an impedance plane. The approximate solution for the sound field behind an infinitely long barrier is given by

$$\phi\left(\mathbf{r}_R, \mathbf{r}_S\right) = -2 \int_{z=z_1}^{z=+\infty} \int_{y=-\infty}^{y=\infty} \phi_L\left(\mathbf{r}_0 | \mathbf{r}_S\right) \frac{\partial \phi_L\left(\mathbf{r}_R | \mathbf{r}_0\right)}{\partial x_R} dy dz \tag{1}$$

where, $\mathbf{r}_S$, $\mathbf{r}_R$ and $\mathbf{r}_0$ indicate the position of source, receiver and barrier surface receptively. The symbols $\phi_L(\mathbf{r}_0|\mathbf{r}_S)$ signifies the sound field at the barrier plane ($\mathbf{r}$=$\mathbf{r}_0$) due to the source locating at $\mathbf{r}$=$\mathbf{r}_S$ and $\phi_L(\mathbf{r}_R|\mathbf{r}_0)$ represents the sound field at the receiver ($\mathbf{r}$=$\mathbf{r}_R$) due to the source locating at the barrier plane, $\mathbf{r}$=$\mathbf{r}_0$. The computation of ϕ_L is straightforward as the Weyl-Van der Pol formula can be used,

$$\phi_L = \frac{e^{ikR_1}}{4\pi R_1} + Q\frac{e^{ikR_2}}{4\pi R_2} \tag{2}$$

where Q is the spherical wave reflection factor, R_1 is the direct ray path and R_2 is the specularly reflected ray path. An interesting situation arises if the barrier height is reduced to zero, *i.e.* in the absence of a barrier, then

$$\phi(\mathbf{r}_R, \mathbf{r}_S) = \phi_L(\mathbf{r}_R, \mathbf{r}_S) = -2\int_{z=0}^{z=+\infty}\int_{y=0}^{y=\infty} \phi_L(\mathbf{r}_0|\mathbf{r}_S)\frac{\partial \phi_L(\mathbf{r}_R|\mathbf{r}_0)}{\partial x_R}dydz \tag{3}$$

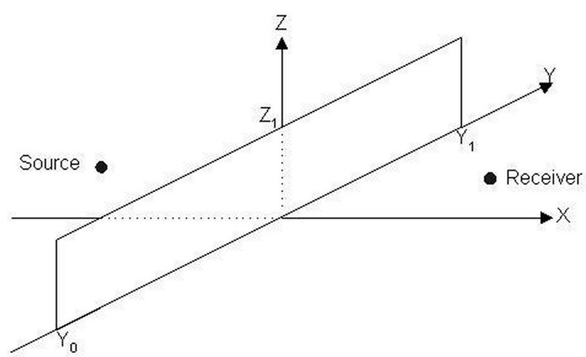

Figure 1: Geometry of source, receiver and screen; the screen is in the plane x=0: $Y_0 \le y \le Y_1$ and $0 \le z \le Z_1$; the plane z=0 is an impedance boundary.

This implies that the sound field above a homogeneous impedance ground can be approximated by a double integral as shown in the right side of equation (3). The accuracy of such an approximation will be demonstrated in Section 4. Taking the same approach as Thomasson and Rasmussen, we can generalize the scheme to compute the sound field behind a finite size barrier (with or without gaps) as follows:

$$\phi(\mathbf{r}_R, \mathbf{r}_S) = -2\int\int_{\Gamma-\Gamma_{\mathrm{B}}} \phi_L(\mathbf{r}_0|\mathbf{r}_S)\frac{\partial \phi_L(\mathbf{r}_R|\mathbf{r}_0)}{\partial x_R}dydz \tag{4}$$

where Γ is the semi-infinite plane containing the barrier surface, as indicated in the integral of equation (3). The symbol Γ_{B} represents the barrier surface only. Dividing the integral into two terms, the sound field can be computed by

$$\phi(\mathbf{r}_R, \mathbf{r}_S) = \phi_L(\mathbf{r}_R, \mathbf{r}_S) - \left[-2\int\int_{\Gamma_{\mathrm{B}}} \phi_L(\mathbf{r}_0|\mathbf{r}_S)\frac{\partial \phi_L(\mathbf{r}_R|\mathbf{r}_0)}{\partial x_R}dydz\right] \tag{5}$$

where equation (3) has been used in equation (4) to replace part of the double integral by the analytical solution given in (2). Hence, the sound field behind a thin barrier can be evaluated directly that involves the use of the Weyl-Van der Pol formula and a numerical integration for the reduced area of Γ_{B} rather than $\Gamma - \Gamma_{\mathrm{B}}$. The problem can be simplified considerably if we restrict the investigation to a two-dimensional case such that the thin barrier is infinitely long and has a constant height. In the high frequency limit, we can evaluate the inner integral (with respect to y) by means of the method of stationary phase to yield

$$\begin{aligned}\phi(\mathbf{r}_R, \mathbf{r}_S) = \phi_L(\mathbf{r}_R, \mathbf{r}_S) - X_R\sqrt{8\pi k}\frac{e^{-i\pi/4}}{16\pi^2}\int_{\Gamma_{\mathrm{B}}} &\left[\frac{e^{ik(R_1+R_3)}}{\sqrt{R_3^3 R_1(R_1+R_3)}} + \frac{Q_2 e^{ik(R_1+R_4)}}{\sqrt{R_4^3 R_1(R_1+R_4)}}\right.\\ &\left.+\frac{Q_1 e^{ik(R_2+R_3)}}{\sqrt{R_3^3 R_2(R_2+R_3)}} + \frac{Q_1 Q_2 e^{ik(R_2+R_4)}}{\sqrt{R_4^3 R_2(R_2+R_4)}}\right]dx\end{aligned} \tag{6}$$

where R_1, R_2, R_3, and R_4 are respectively the direct and reflected rays located in the vertical plane containing source and receiver and X_R is the shortest distance between receiver and barrier (see Figure 2). The spherical wave reflection coefficients Q_1 and Q_2 are calculated on the basis of ground impedance on the source side and receiver side respectively. The integral limits, Γ_B of equation (6) specify the height of the thin barrier at the horizontal plane containing the source and receiver.
The use of equations (5) and (6) are preferred because of the area required for numerical integration is generally smaller than those suggested in Refs. [7] and [8]. Hence, in general, less computational resources are required for the evaluation of the sound fields behind a thin barrier

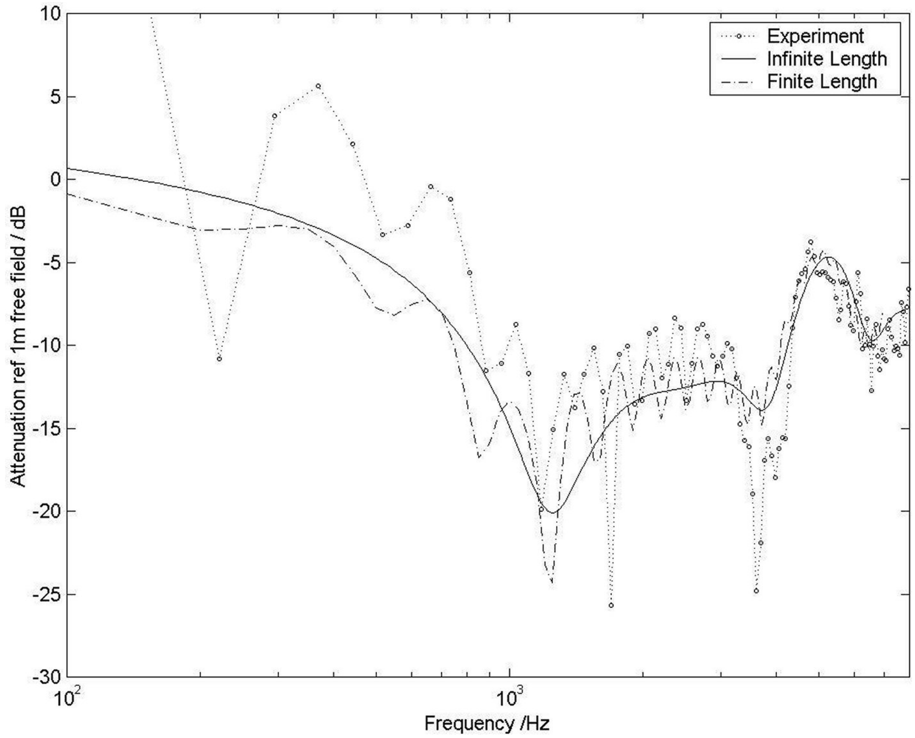

Figure 2: The direct and reflected ray located in the vertical plane containing source and receiver.

3 - EXPERIMENTS

Experiments were carried out in an anechoic chamber with an effective size of 6 × 6 × 3 (height) m. The attenuation of the barrier was measured by a Maximum Length Sequence System Analyser (MLSSA). A low-end PC computer with 32 MB Ram memory installed with MLSSA card was used. The source was connected to a MLSSA card through an amplifier (B&K 2713). A BSWA TECH MK224 microphone together with BSWA TECH MA201 preamplifier was used as a receiver. The microphone was connected to the MLSSA card through a BSWA TECH amplifier MC102. Two sets of measurements were conducted with different configurations as follows:

1. Finite size barrier with a horizontal gap − the barrier used was made of a thin hard wood board of 0.26 m height and 2.44 m long. The barrier was raised up 0.018 m above the ground so that the effective height of the barrier was 0.278 m with a gap of 0.018 m. The total area of the gap was approximately 6.5% of the total area of the barrier. The source and receiver were placed at the middle of the barrier and the height of the gap was measured from the hard ground.

2. Finite size barrier with a vertical gap − the barrier used was made of two hard wood boards with size 0.26 m height and 2.44 m long. The barriers were placed adjacent to each other and a gap was left at between the barriers. The size of the barrier was approximately 0.26 m × 4.91 m. The source and receiver plane was perpendicular to the barrier and placed at the middle or offset from the barrier gap.

4 - RESULTS AND DISCUSSIONS

It is apparent from equation (3) that the sound field due to a point source above a flat impedance ground may be represented by a double integral. In principle, the sound field can be computed directly by evaluating the double integral numerically. However, Weyl-Van der Pol formula [equation (2)] is normally used in most practical situations. To confirm that the validity of replacing the double integral with equation (2), we show a comparison of the sound fields predicted by these two computational schemes in Figure 3. The agreements are excellent in general. This gives us the confident of changing the area of integration from $\Gamma - \Gamma_B$ to Γ_B which leads to a significant reduction of computational time. This is particularly important when we consider a finite-size barrier. In Figure 3 and subsequent plots, the attenuation versus frequency was used where the attenuation was defined as the total sound field with reference to the free field measurements at 1 m.

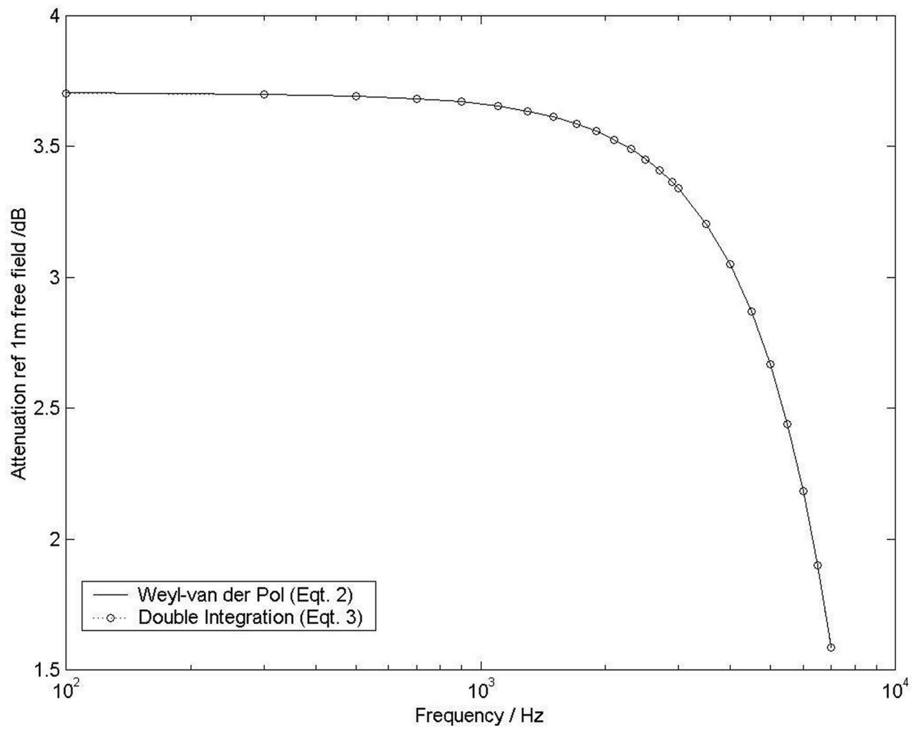

Figure 3: Comparisons of two numerical schemes in computing sound fields.

The prediction and experimental data for a barrier with a horizontal gap are shown in Figure 4. The source height and receiver heights are 0.065 m and 0.105 m, respectively. The distance for the source and receiver from the barrier are 0.5 m and 0.8 m respectively. It can be seen that the numerical results for a finite length barrier agree reasonably well with experimental data, especially the interference patterns at high frequencies. Numerical predictions for the two-dimensional model are also presented in Figure 4. However the predicted results are less satisfactory but the general trend is well predicted by the two-dimensional model. This is because sound diffracted at the vertical edge on both ends of the finite length barrier is not predicted by this two-dimensional model. The interference of sound due to vertical edges is particularly important at high frequencies and short barrier lengths. Numerical simulations using equation (5) are carried out with different barrier lengths but their numerical results are not shown here for brevity. Nevertheless, it can be demonstrated that the 'edge effect' is less significant if the barrier length is extended to the distance greater than 70 times the wavelength of interest at either side.

The predictions and experimental measurements for a barrier with a vertical gap are shown in Figures 5 and 6. The width of the vertical gap, the source and receiver heights, the distance from the source to the barrier and the distance from the barrier to the receiver are 0.03 m, 0.045 m, 0.045 m, 0.3 m and 0.6 m respectively. The experiments were performed over a hard wood board covered with a carpet in which Attenborough's two-parameter model [9] was used to characterize the acoustical properties of the impedance ground. Pre-measurement characterization was conducted. The best-fit parameters for the carpet are 10 kPa s m^{-2} for the effective flow resistivity and 10 m^{-1} for the effective rate of change of porosity with depth. Again numerical predictions agree reasonably well with experimental measurements. The experiments are arranged such that the source and receiver, which are placed at the either side of a finite length barrier, can 'see' each other. Under these stringent conditions, other numerical models [4,5] cannot be used but equation (5) may be used instead to predict the sound field with reasonable accuracy.

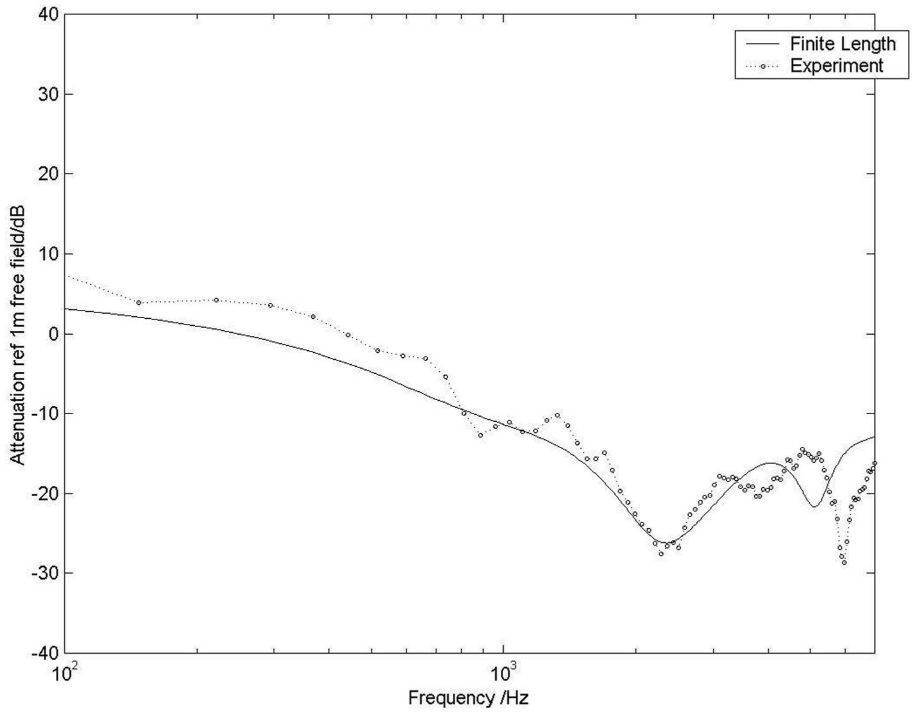

Figure 4: Attenuation of barrier with horizontal gap.

We wish to point out that the methods presented may be used in many practical situations. For instance, the spherical wave reflection coefficients Q_1 and Q_2 can be different. This is suitable for the case, for example, the road surface is hard on the source side and soft [e.g. grassland] on the receiver side.

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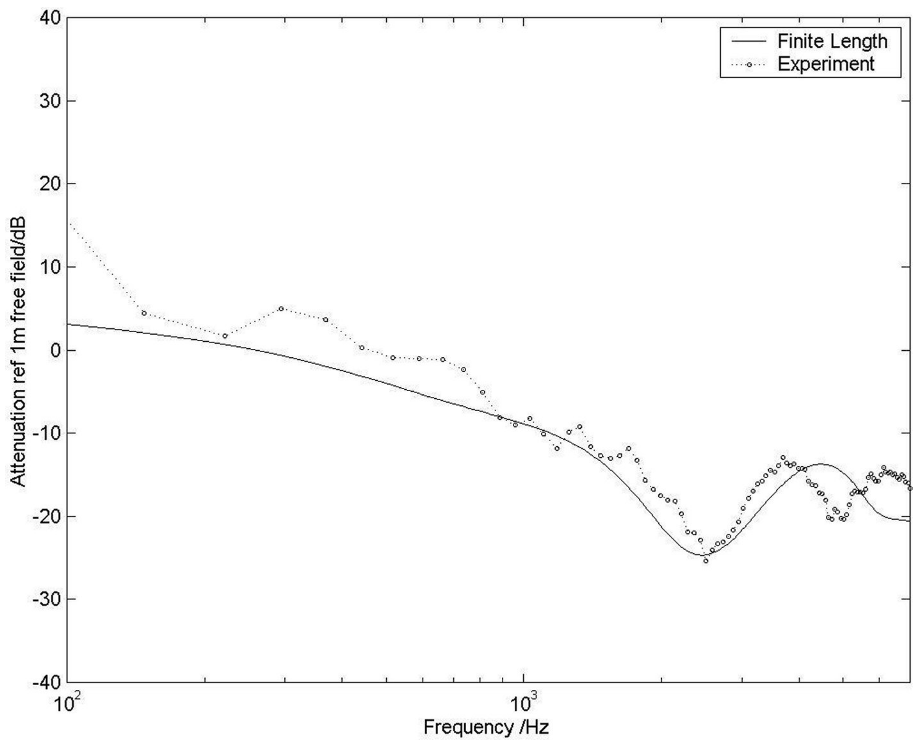

Figure 5: Attenuation of barrier with vertical gap (0.03 m width, no offset).

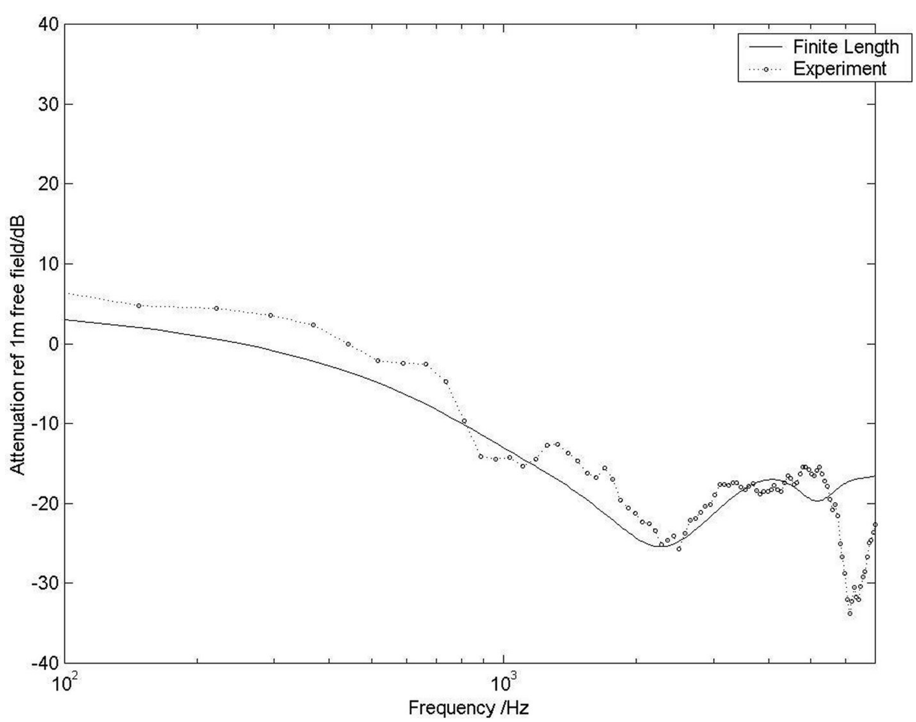

Figure 6: Attenuation of barrier with vertical gap (0.03 m width, 0.1 m offset).