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THE THEORETICAL MODEL TO OPTIMIZE NOISE BARRIER PERFORMANCE AT THE WINDOW OF A HIGH-RISE BUILDING

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This paper attempts to design the horizontal noise barrier near the window at the building facades. Previous results have showed that the insertion loss by the barrier declines for the occurrence of reflection. In this paper, some remedial measures have been studied using the theoretical prediction by Macdonald's and the image receiver theory. The theoretical model results were verified by the scale models tests. By designing an absorptive top screen using the theoretical models, an insertion loss of 17 dB at a frequency of 500 Hz, 20 dB, at a frequency of 1000 Hz and 25 dB and at frequency of 2000 Hz could be obtained. Such performances are higher than the previous windows screens and are comparable with tall barriers or partial enclosures on the roadside. This is particularly useful in high-rise buildings when tall barriers cannot be built.

1. INTRODUCTION

Hong Kong is one of the most densely populated cities in the world. Due to the scarcity of land, it is common that high-rise residential buildings are built close to the traffic road [1, 2]. Barriers are often utilized as a means of traffic noise measure. However, the unacceptable higher traffic noise still affects the upper part of buildings where the level is higher than the shadow zone of the barriers. Increasing the barrier height will require unacceptable cost and one alternative is to provide noise screening at the residents's window.

Recently, a number of research papers analyzing the implemented traffic noise abatement measures at the receivers have been published. Field and Fricke [3] tried to analyze the attenuation of noise entering buildings by placing a quarter-wave resonator system outside the building ventilation openings. However, it was only effective for narrow bandwidth.

Cheung *et al.* [4] studied the barrier attenuation of road traffic noise to the balconies in a high-rise residential building. The average measured noise reduction provided by the balconies with reflective ceiling was only 1·6 dB. If the balcony was without ceiling, an additional 5 dB reduction would be obtained. It implies that the degradation due to reflection must be considered.

While there are some numerical studies of balconies as barriers [5–8], very few extensive studies of window screens were found. This paper will consider the use of horizontal screens near the window to achieve barrier attenuation. A lintel is a flat canopy placed over windows that can be used in high-rise buildings to rectify the limitation of roadside noise barriers. The basic idea of adding a lintel is similar to that of installing a barrier at the

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building. The lintel is placed at the top of a fixed window and forms a screen for the ventilation window. It allows natural ventilation of buildings while providing some reduction of external noise levels inside buildings (see Figure 1(b)). Traffic noise cannot transmit into the building directly. The advantages of using lintels for this purpose include the relatively low cost of installation compared with other measures, and minimal maintenance requirements. Scale model tests were used to study the effects of absorption materials on the acoustic performance. A theoretical model has been applied to predict the performance of noise reduction. The mathematical theories of prediction are based on the equations of Macdonald [9], who derived a solution to the half-plane diffraction problem in a spherical sound field.

2. METHODOLOGY

The scale model test was divided into two parts. It was undertaken in a semi-anechoic room to simulate the free-field conditions and reduces the unwanted reflection. The first part used a model with a scale of 1 : 10 to test the effects of reflecting surface above the screen on the barrier attenuation. The second part used a full-scale model to analyze the improvement of noise reduction when absorptive material is provided on the screen itself.

2.1. SCALE MODEL TEST (1 : 10)

A scale of 1 : 10 was used as a scaling factor to prepare the model. The noise source was generated by 12 loudspeakers which were connected to two different signal generators and contained in a rectangular box with air gaps of 25 mm × 2·2 m at the bottom (see Figure 1(a)). The advantage of facing the sources to the floor is to enhance the multiple reflection between the speakers and the floor. It generates a diffused source from the gap and reduces the directional effect.

To minimize the noise interference from these loudspeakers, they were installed at different orientations in the box and every alternative loudspeaker was connected to a signal generator to ensure that the signal generated from the loudspeaker was different from the next one. The benefit of using loudspeakers as a noise source is that the loudspeakers can provide a stable line source.

The scale model was made of cardboard paper. The top of the lintel was reinforced with loaded vinyl to increase sound insulation. A number of scenarios were tested for five angles of incidence (15, 30, 45, 60 and 75°).

The noise source signal was white noise with the frequency ranged from 1 to 12·5 kHz. The frequency of 5 kHz is a simulation of the (500 Hz) dominant traffic noise frequency measured for the analysis. Before the measurement, two-signal generators had to be adjusted to a similar level at all specific bands and ensured that the noise source was atleast 30 dB above the background for the band of interest.

The measurement was taken for a 1 min period at two positions, on the left- and the right-hand side of the recessed window, and was analyzed by HP 3569A real-time frequency analyzer (see Figure 1(b)). Another sound level meter was used for the measurement throughout the testing period, to ensure the magnitude of the signal-generated constant.

2.2. FULL-SCALE MODEL

A 1 : 1 scale model was used to analyze the improvement of insertion loss by the absorptive material provided on the lintel. This test focuses on the performance of providing

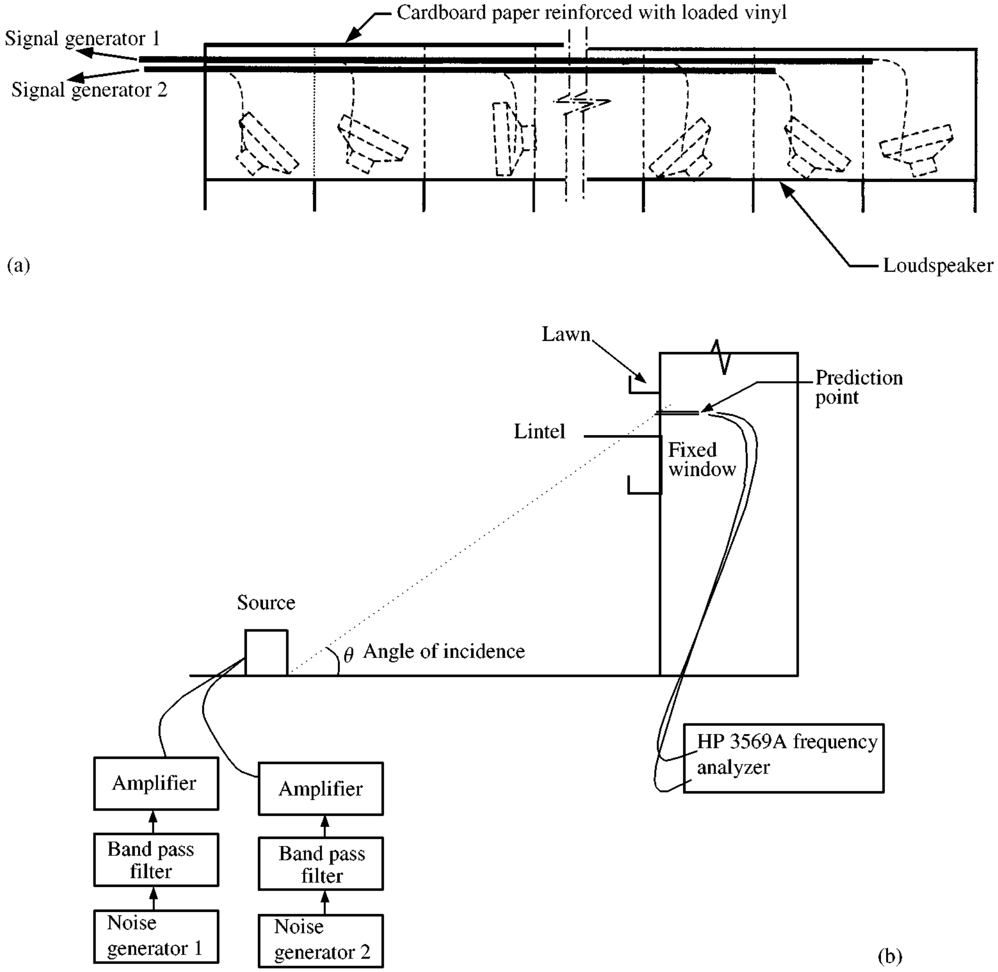

Figure 1. (a) Detail drawing of rectangle loudspeakers; (b) elevation of lintel model.

absorptive material on the top of the screen to reduce diffraction. The scale model was made of plywood. A number of scenarios were tested, each for seven angles of incidence (5, 15, 30, 45, 60, 75 and 90°).

A loudspeaker was used to generate the noise source. The source was located at the middle of the window. The signal was a white noise with the frequency ranged from 200 Hz to 5 kHz. The frequencies of 500 Hz, 1 kHz and 2 kHz were measured for analysis.

The measurement was taken for a 1 min period at two positions, the inside and the outside of the window and was analyzed by the HP 3569A real-time frequency analyzer.

3. THEORETICAL ANALYSIS

In this study, a theoretical model has also been applied to model the insertion loss of a lintel. The basic theories of the model follow Macdonald's solution that uses the mathematical analysis to derive a solution for estimating the diffraction problem in a spherical sound field. Fujiwara *et al.* [10, 11] modified this solution to estimate the effect of diffraction at absorptive barriers:

$$D1 \equiv \frac{\exp(-\mathrm{i}\pi/4)}{\pi^{1/2}}$$

$$\times\left(\frac{2^{1/2}\times\exp(\mathrm{i}kR_1)}{(S(R_1+S))^{1/2}}\int_{w1}^{\infty}\exp(\mathrm{i}v^2)\,\mathrm{d}v + R\times\frac{2^{1/2}\times\exp(\mathrm{i}kR_2)}{(S(R_2+S))^{1/2}}\int_{w2}^{\infty}\exp(\mathrm{i}v^2)\,\mathrm{d}v\right),$$

where A is the shorter distance from source to edge of screen, B the shorter distance from edge of screen to receiver, (Refer Figure 3(a) for configuration), i the complex number, k the wave number, and R the reflection coefficient,

$$S = A + B,$$

$$R_1^2 = A^2 + B^2 - 2AB\cos(\Theta + \theta),$$

$$R_2^2 = A^2 + B^2 - 2AB\cos(\Theta - \theta),$$

$$w1 = -\left(\frac{4kAB}{S+R_1}\right)^{1/2}\times\cos\frac{1}{2}(\Theta+\theta), \qquad w2 = \left(\frac{4kAB}{S+R_2}\right)^{1/2}\times\cos\frac{1}{2}(\Theta+\theta),$$

$D1$ is the sound pressure in the receiver,

$$D = \frac{\exp(\mathrm{i}kR_1)}{R_1} \quad \text{(spherical sound wave)},$$

Insertion loss $= D1 - D$.

4. MEASUREMENT RESULT (SCALE 1 : 10 MODEL)

From Figure 2, we can see that the efficiency of a lintel for traffic noise protection depends on the angle of incidence of the source to the receiver and the depth of a lintel. At 15–45°, the level of noise attenuation increased with the angle of incidence, and also as the depth of

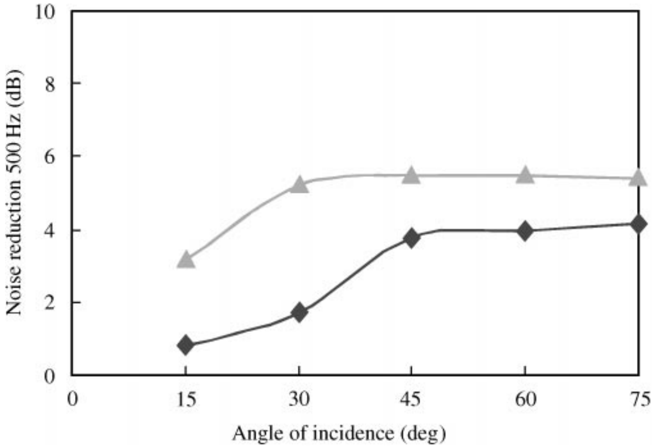

Figure 2. The insertion loss of lintel as variation of angle of incidence. ◆, 625 mm; ▲, 1200 mm.

a lintel increases, the insertion loss will increase. However, the noise attenuation decreases as the angle of incidence increases up to 60°. It is because some noise contributes from the reflection by the bottom of the lawn of the upper floor. At that angle, increase the depth of a lintel, the reflection areas also increase, the reflection effect will become more serious.

To rectify the reflection effect by the top face of a lintel and the bottom face of a lawn. Two types of measures can be used, providing absorptive material over the surface of faces or inclining the angle of bottom faces of the lawn (Figure 3). The basic concept of inclining the bottom surfaces of a lawn is to decrease the power of reflection source and the diffuse energy components decrease. Figure 4 shows the performance at an angle of incidence at 60 and 75° at which a higher reflection effect occurred.

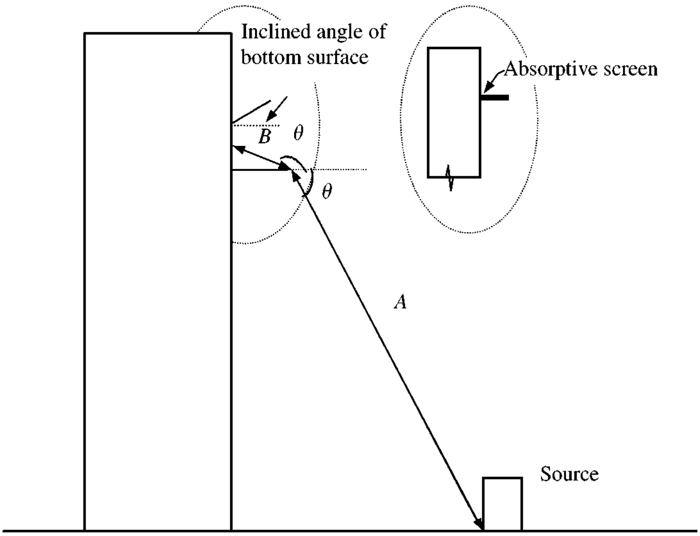

Figure 3. Elevation of acoustic scale model.

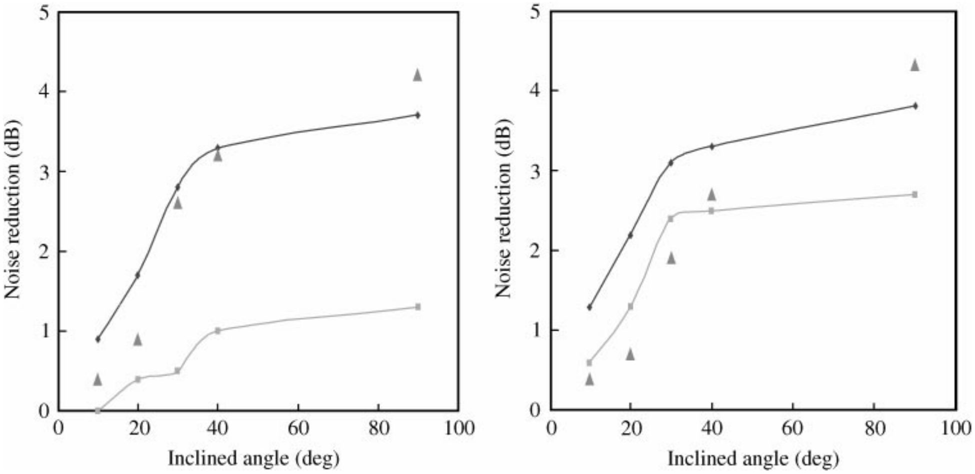

Figure 4. Reduction of noise reflection by the variation of inclined angle of bottom surface: (a) Angle of incidence 60°; (b) Angle of incidence 75°. ■, DS 625 mm; ◆, DS 1200 mm; ▲, CDS 1200 mm.

TABLE 1

Noise reduction performance of lintel as a variation of angles of incidence

Angles of incidence (deg)	Depth of lintel		
	0 mm	625 mm	1200 mm screen
75°	70·9 dB	66·7 dB	65·5 dB
60°	76·5 dB	72·5 dB	71 dB
45°	78·6 dB	74·8 dB	73·1 dB
30°	80·5 dB	78·8 dB	75·3 dB
15°	81·5 dB	80·7 dB	78·3 dB

TABLE 2

Noise reduction performance of lintel as a variation of angles of bottom surface

Angle of bottom surface (deg)	Angle of incidences			
	60°		75°	
	DS 625 mm	DS 1200 mm	DS 625 mm	DS 1200 mm
0	57·2 dB	60·8 dB	54·5 dB	51·7 dB
10	57·2 dB	59·5 dB	53·9 dB	50·4 dB
20	56·8 dB	59·1 dB	53·2 dB	49·5 dB
30	56·7 dB	58·0 dB	52·1 dB	48·6 dB
40	56·2 dB	57·4 dB	52·0 dB	48·4 dB
90	55·9 dB	57·1 dB	51·8 dB	48·0 dB

Note: DS, depth of screen; C, computer model result.

From Figure 4, additional noise reduction is found for various inclined angles of the bottom of the lawn. The reduction of noise reflection by inclining the bottom angle for a 625 mm deep lintel is not noticeable. It is because the noise reflection in these depths of surface is lower. As the depth of a screen is increased to 1200 mm, their improvements of noise reduction become conspicuous. About 3 dB of additional noise reduction could be obtained when the angle of the bottom surface of the lawn is rotated at 30°. It can be concluded that the optimal inclined angle of the bottom surface is around 30°. On further increase of the angle of inclination, the noise reduction increased just a little bit.

The prediction result by the image receiver model (Appendix A) derived from reference [12] is shown in Figure 4. The trends of the theoretical noise reduction are in agreement with those of the scale model.

5. MEASUREMENT RESULT (SCALE 1 : 1 MODEL)

To analyze the efficiency of providing an absorptive material on the top of the screen, the measurement was carried out in 1 : 1 acoustic scale model with one source (Figure 5). The advantage of using the scale of 1 : 1 model is that it can simulate the actual acoustic absorption efficiencies of the material at each frequency band. It cannot be similated by the 1 : 10 scale model. However, the shortcoming of using a full-scale model is the limitation of

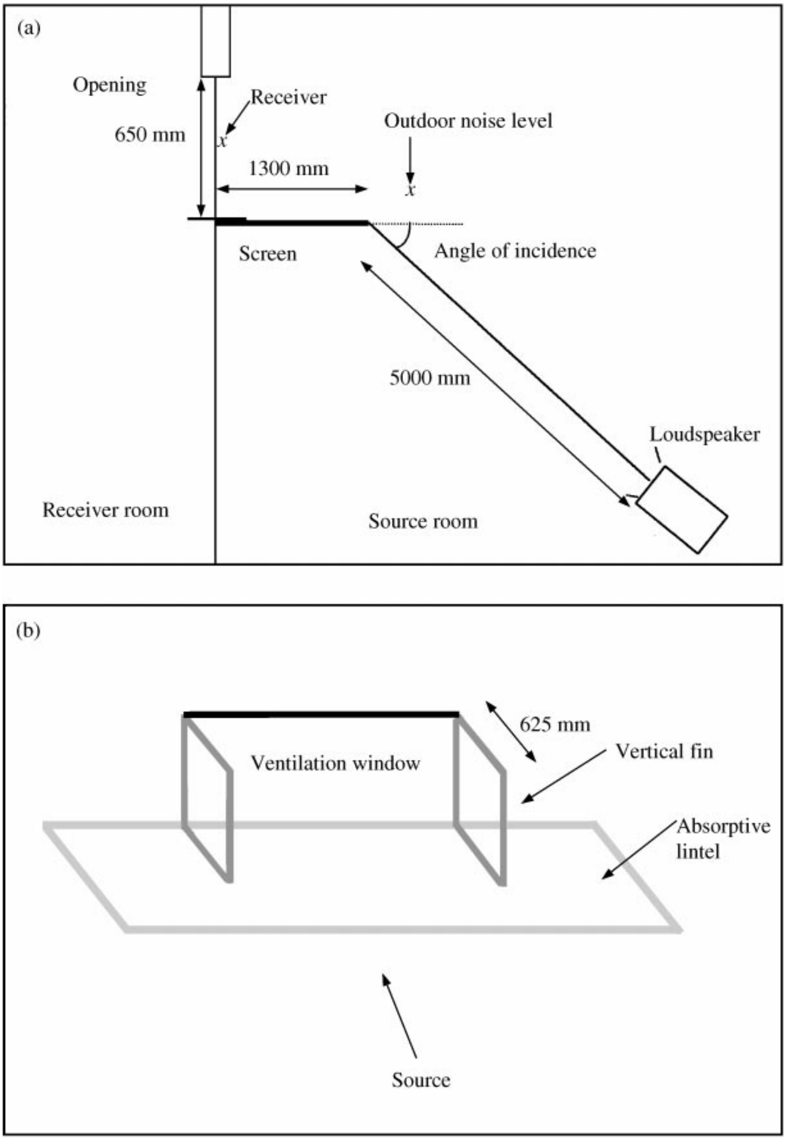

Figure 5. (a) Measurement of local opening with screen using loudspeaker; (b) detail drawing of ventilation window.

space of the laboratory. It should only provide the point source from the single loudspeaker. The angle of view of the window was limited by the vertical fins on both sides of the lintel.

Before the performance of an absorptive screen were analyzed, the insertion loss by two scale factors models has been compared (Figure 6).

In Figure 6, the measured results of insertion loss by two scale factors models differed constantly by about 1 dB. It is shown that the measurement results by the two models have no significant variation when the scale factors are changed, and it implies that 1 : 1 model can represent the actual effects of a line source by limiting the angle of view of the window.

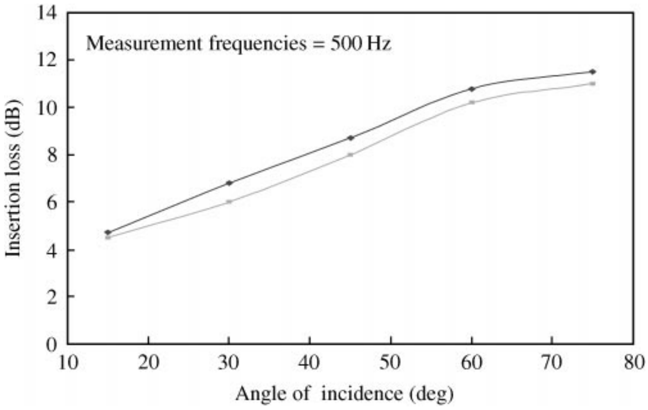

Figure 6. Comparison of the measurement result by two scale factors model: ■, 1:10 model; ◆, 1:1 model.

6. COMPARISON OF THE RESULT FROM THE SCALE MODEL AND THE THEORETICAL MODEL

In Figure 7, the results of the insertion loss of 1·3 m deep reflective screen acoustical full-scale modelling have been compared against that of the theoretical predictions. In Figure 7(a) and 7(b), the performances of insertion loss by the lintel at 500 Hz and 1 kHz in 1/3 octave bands were analyzed. We found that the trends of insertion loss, which were estimated by the two models, had a good agreement. The differences in the two curves are normally less than 1 dB. However, the predicted insertion loss result is much higher than the measured result at 2 kHz. It may be due to the interference effect of reflection.

6.1. WIDE ABSORPTIVE EDGE SCREEN (FIGURE 3(b))

The wide absorptive edge of the absorptive screen produced the additional attenuation shown in Figure 8(a)–8(c). In this figure, the results of the acoustical scale modelling were also compared with that of the theoretical computer model. It is found that the theoretical reduction trends are in agreement with those of the scale model.

The absorption coefficient of this absorptive material was measured by the impedance tube test, and the result is 0·5 for 500 Hz, 1 for 1 and 2 kHz. In Figure 8(b) and 8(c), it is found that the added attenuation is about 4–6 dB higher than that for the conventional screen at 1 and 2 kHz. However, in Figure 8(a), despite its absorptivity, it produced a low added attenuation at 500 Hz for some angle of incidence probably due to the lower absorption coefficient. Moreover, the length of the absorber is also an important criterion influencing the absorption. As the equation $c = f\lambda$ and the speed of sound is around 340 m/s, the wavelength of 500, 1000 and 2000 Hz is 0·68, 0·34 and 0·17 m, respectively. Rawlins [13] derived that the absorbing material that comprises the edge need only be of the order of a wavelength long to have approximately the same effect, on the sound attenuation in the shadow side of the barrier, as a completely absorptive barrier. From the theories above, the length of the absorptive screen must be at least 0·68 m for 500 Hz and 0·34 m for 1000 Hz.

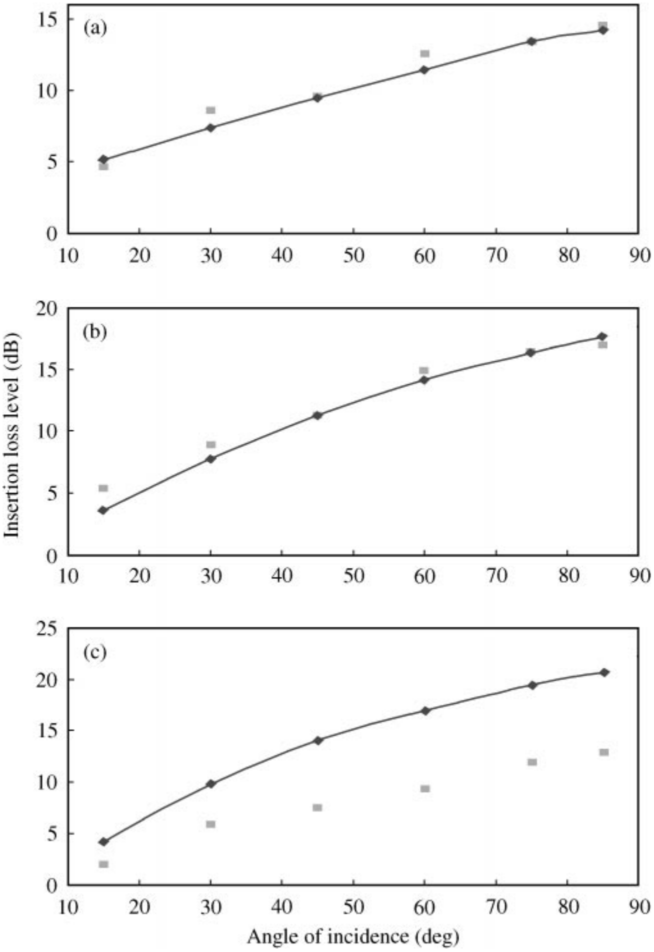

Figure 7. Comparison of the insertion loss level predicted by the scale model with that by theoretical model: (a) frequencies of measurement = 500 Hz; (b) frequencies of measurement = 1000 Hz; (c) frequencies of measurement = 2000 Hz. ■, scale model; ◆, theoretical model.

7. CONCLUSION

In this paper, the image receiver model was used in combination with Macdonald's diffraction theory to predict the performance of barriers near the window. The average measured noise reduction provided by the lintel model with reflective surface was about 3–5 dB. The sound reflected from the bottom of the reflecting surface at the upper floor was found to be the dominant component leading to the degraded performance of lintel at a large angle of incidence. To solve the reflection problem, remedial measures using diffusion have been predicted using the image receiver model and verified by the test. About 3 dB additional noise reduction could be obtained when the bottom faces of the lawn were rotated for 30° or higher.

Secondly, the Macdonald's diffraction theory was used in the lintel design. The comparison of theoretical result and scale model result is in good agreement. This showed that the Macdonald's theory could be used for the design of absorptive barrier. Using

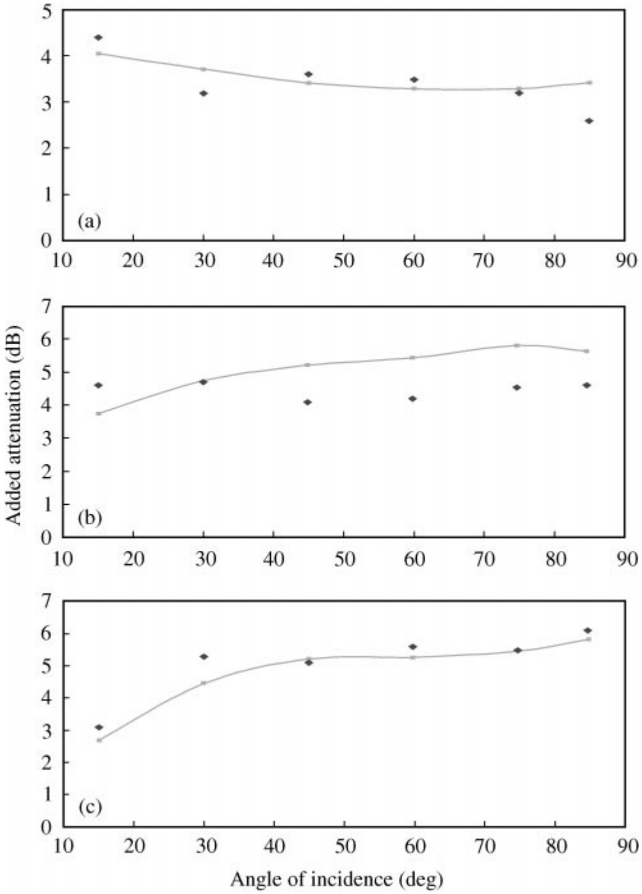

Figure 8. Additional attenuation of the lintel by absorption material: (a) measurement frequency = 500 Hz; (b) measurement frequency = 1000 Hz; (c) measurement frequency = 2000 Hz. ■, scale model; ◆, theoretical model.

a lintel with an absorptive top screen, an insertion loss of 17 dB at a frequency of 500 Hz could be obtained. Such performances are comparable with those of tall barriers or partial enclosures on the roadside. The design must be based on the new prediction method using image-receiver model to eliminate reflection effects. Then the Macdonald's equation can be used to estimate the absorption improvement.

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APPENDIX A

A.1. PREDICTION OF NOISE REDUCTION DUE TO INCLINED BARRIER (LAWN)

A.1.1. Prediction of insertion loss (Figure A1)

The Maekawa prediction is in terms of the Fresnel number N, given by

$$N = \frac{2\delta}{\lambda}. \tag{A.1}$$

The path difference δ, the difference between the shortest path over the barrier and the direct path, is given by

$$\delta = SB + BR - SR \tag{A.2}$$

and λ is the wavelength.

As given in reference [1], when $Y > Ys$ (illuminated region), the barrier attenuation ΔL_0 is given by

$$\begin{aligned} &\Delta L_0 = 0\,\mathrm{dB}, \quad \text{for } N' > 1{\cdot}0972, \\ &\Delta L_0 = -\left[5 + 20\log\left(\frac{N'}{\tan N'}\right)\right]\mathrm{dB} \quad \text{for } N' \leqslant 1{\cdot}0972, \qquad \text{(A.3)} \\ &N' = (2\pi N)^{0{\cdot}5}. \end{aligned}$$

When $Y \leqslant Ys$ (shadow region), then

$$\Delta L_0 = -\left[5 + 20C_1 \log\left(\frac{N'}{\tanh(C_2 N')}\right)\right] \text{dB} \quad \text{for } N' \leqslant 10, \tag{A.4}$$

$$\Delta L_0 = -20\,\text{dB} \quad \text{for } N' > 10.$$

The coefficients C_1 and C_2 modify the size of source. In this program, a line source is used: $C_1 = 0{\cdot}75$ and $C_2 = 1{\cdot}00$.

The attenuation due to distance is

$$L = -10 \log_{10}\left(\frac{SR}{13{\cdot}5}\right). \tag{A.5}$$

The total noise reduction from S to R is

$$L_0 = L + \Delta L_0. \tag{A.6}$$

A.1.2. Prediction of reflection by the image receiver model (*Figure A*1)

Due to the existence of two shadow zones (arising from the upper barrier and the lower barrier), the virtual receiver produces two critical values $Ys1$ and $Ys2$, and the two path differences

$$\delta_1 = SB + BR' - SR', \tag{A.7}$$

$$\delta_2 = SB1 + B1R' - SR'. \tag{A.8}$$

Let $Yz = (Ys1 + Ys2)/2$, if $Yz \geqslant Y$ then $\delta = \delta_1$ else $\delta = \delta_2$.

When $Y \geqslant Ys1$ or $Y < Ys2$, the barrier attenuation ΔL_1 is given by equation (A.4). When $Ys1 \geqslant Y > Ys2$, ΔL_1 is given by equation (A.3).

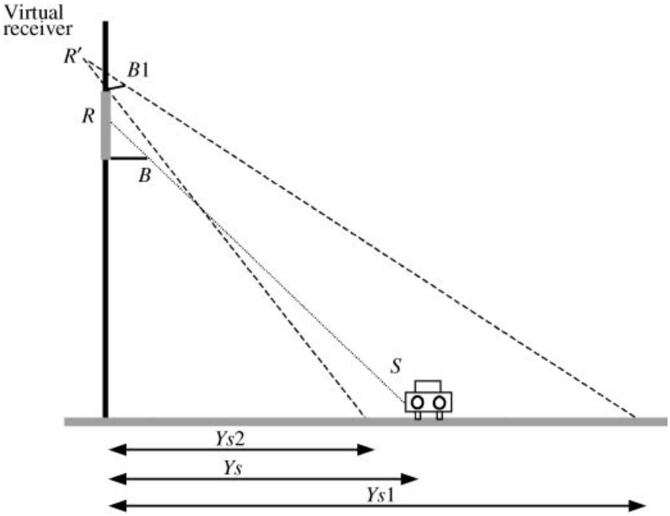

Figure A1. Configuration of image receiver.

Combining the distance and the barrier effect, the total attenuation due to the second barrier is

$$L_1 = -10\log_{10}\left(\frac{SR'}{13{\cdot}5}\right) + \Delta L_1. \tag{A.9}$$

Then the new attenuation due to the two barriers is

$$L_2 = 10\log_{10}(10^{L_0/10} + 10^{L_1/10}). \tag{A.10}$$

The degradation due to the second barrier is

$$D = L_2 - L_0. \tag{A.11}$$

Reduction of inclined barrier = D (inclined barrier) − D (horizontal barrier).