A SCALE MODEL INVESTIGATION OF THE ROLE OF DIFFUSE REFLECTIONS IN URBAN NOISE PROPAGATION

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1 INTRODUCTION

Building facades tend to consist largely of smooth areas of masonry incorporating features such as windows, doors, balconies and a variety of architectural details. Reflected sound will tend to be scattered from regions where there is a change in dimension or surface impedance thus a façade will act like a plane specularly reflecting surface on which there are localised diffusers. Until recently the majority of urban noise prediction models were based upon one of two hypotheses[1]. The first is that building facades reflect sound purely specularly and the second is that they reflect sound purely diffusively. Recent attempts to model mixed specular and diffuse reflections from facades ignore the detail of façade reflections and model them by simply assuming that a fraction of the reflected energy can be treated as being reflected diffusely whilst the remainder is reflected specularly.

Neglecting the effect of façade absorption, two reflection coefficients can be defined: the specular, **s**, and the diffuse, **d,** where **s + d** = 1. There is very little data available regarding the reflection properties of building facades, however, the results of work by Steenackers et al[2] Donavan and Lyon[3] and Heutschi[4] suggest that the proportion of sound energy reflected diffusely from a building façade is small and that the value of **d** is low and of the order of 0.2.

This paper describes a scale model investigation of sound reflection from facades having a similar degree of surface irregularity to those of typical buildings. Two methods of obtaining a value of **d** are investigated, one method involved measurements relating to low orders of reflection and the other to higher orders of reflection.

2 CHARACTERISTICS OF NOISE PROPAGATION IN URBAN AREAS

Considering a point source of sound in a simple street channel, the second order of reflection will have a reflection history with the following components: **ss (**specular specular), **sd** (specular diffuse), **ds** (diffuse specular), and **dd** (diffuse diffuse) where **s** denotes specular and **d** diffuse reflections and the sequence of the symbols indicates the sequence of reflections. Reflection histories will include configuration factors, $C_F(n)$, as well as products of s and d. This reflection history could be presented in general for a higher order of reflection, ***n***, as:

$$R_H(n) = f((s+d)^n, C_F(n)) \tag{1}$$

The authors have previously employed the image source and radiosity methods to investigate the propagation of sound in a street channel resulting from mixed specular and diffuse reflections[5]. The radiosity method, widely used in applications of heat transfer, was developed to calculate patch-to-patch diffuse reflection. The method was extended to handle ideal specular reflections, which also means that it can be used to handle specular-mixed and diffuse-mixed reflections. This extended radiosity method was modified by the authors to reduce computational requirements. The progression of the reflected sound field for facades having low values of **d** from being dominated by specular reflections to domination by diffuse reflections was demonstrated. This is because with increasing order of reflection, as s<1.0, the purely specular component (s^n) will diminish and mixed specular-diffuse components will increase. These will tend to propagate in a similar way to pure diffuse reflections.

3 THE SIMPLE MODEL

The approach previously employed by the authors can be used at up to the 5th order of reflection but for higher orders it makes system demands, which are excessive, and hence it cannot be used to determine reverberation times. However, assuming that the diffuse coefficient of typical facades is low a simplified procedure can be adopted[6]. In this approach the mixed specular and diffuse reflections histories corresponding to the nth order of reflection are combined into a single reflection of the type $\mathbf{s^{n-1}d}$. In effect, the nth order diffuse reflection component is determined by the illumination of the façade by the (n-1)th specular image of the source. Thus instead of modelling the reflection history as in Equation (1) it can be simplified to:

$$R_H(n) = f((s^n + n(s^{n-1}d)), C_{Fn}) \qquad (2)$$

In this procedure, as there is only one diffuse reflection to be calculated per order of reflection, the processing time will be dramatically reduced. This will enable the effect of higher orders of reflection to be calculated yielding a greater dynamic range and the possibility of calculating parameters determined by high order reflections such as reverberation times. The process combines the multiple exchanges involving diffuse reflections with multiple configuration factors, $C_F(n)$ and single diffuse coefficient d into one simple diffuse reflection with one configuration factor, C_{Fn} , and an effective diffusion coefficient, taken to be the diffuse reflection coefficient of the façade surface.

In the previous approach, the mixed diffuse specular energy that arrives at a receiver is a function of the configuration factors for orders 1 to n and the diffusion coefficient, d. Thus using one configuration factor will introduce a net error that is a function of façade geometry and coefficient d. The temporal spread of diffuse energy resulting from pure diffuse or mixed reflections, will not be shown accurately in the time history, since the spread for a given order of reflection will now be associated with one diffuse reflection rather than a number. However it can be argued that reduction in the tail spread may be compensated for by energy arriving at a higher image order.

An alternative method of modeling mixed specular-diffuse reflections is by means of hybrid computer models. Figure 1 shows a comparison of the Early Decay Time predicted using the simple model and that obtained using RAYNOISE. Although the simple model has been devised on the assumption that **d** is small, agreement between the two sets of data is good even for relatively large values of **d**. It can be seen that the EDT decreases rapidly as the value of **d** increases, apparently tending to the value which would be obtained in the case of surfaces which reflect purely diffusively. Similar effects have been reported in earlier work by the authors[7] and Kang[8].

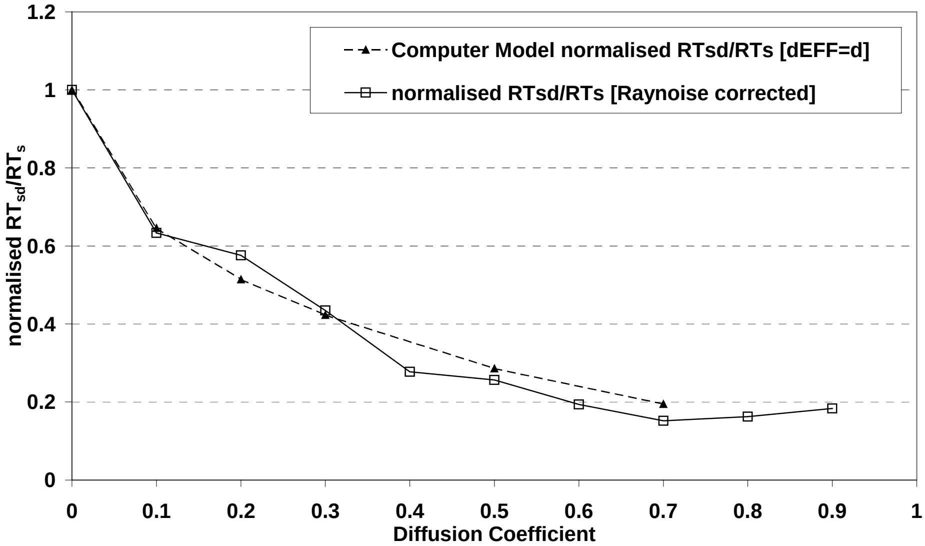

Figure 1: Comparison of EDT obtained using simple model with that obtained using RAYNOISE as a function of **d**.

4 THEORETICAL BASIS OF THE EXPERIMENT

A simplified representation of a source and receiver, both situated on a perfectly reflecting ground plane between two parallel facades, is shown in figure 2. This geometry ensures that the reflections from one façade are identical to those from the opposite façade and also ensures the maximum possible interval between successive specular reflections.

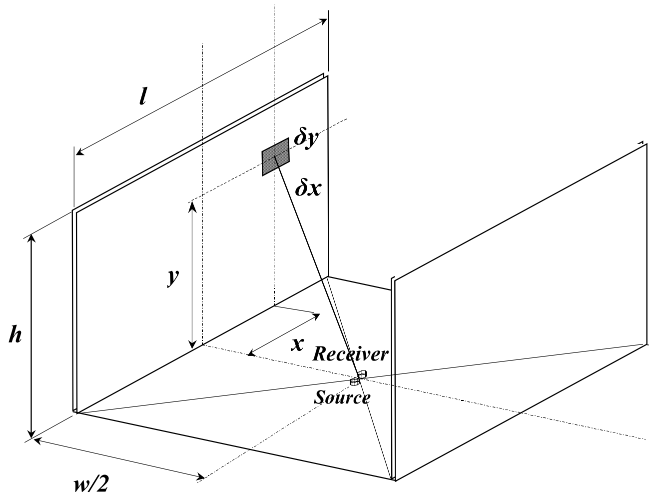

Figure 2: Experimental Configuration

For simplicity, in the following discussion only sound arriving from one façade will be considered. The effect of reflections from the second façade would be to introduce a factor 2 in all steps of the process outlined below but would not affect the result obtained. Assuming that the non-specular component of higher order reflections can be modelled by a simple specular diffuse reflection process, the reflection process is as illustrated in figure 2. The specular intensity at the receiver due to reflections of order n is given by:

$$I_{Sn} = \frac{P(1-d)^n}{2\pi n^2 w^2} \qquad (3)$$

Where P is the source power and the remaining symbols are identified on Figure 2.

The nth order diffuse intensity at the receiver from a patch is the result of illumination by the (n-1)th order specular image source and is given by:

$$\delta I_{Dn} = \frac{P(1-d)^{n-1}(2n-1)dw\delta x\delta y}{8\pi^2\left[x^2+y^2+\frac{(2n-1)^2 w^2}{4}\right]^{\frac{3}{2}}\left[x^2+y^2+\frac{w^2}{4}\right]} \qquad (4)$$

Integrating over façade dimensions yields:

$$I_{Dn} = \frac{P(1-d)^{n-1}d(2n-1)w}{8\pi^2}\int_0^h\int_{-\frac{l}{2}}^{\frac{l}{2}} \frac{dxdy}{\left[x^2+y^2+\frac{(2n-1)^2 w^2}{4}\right]^{\frac{3}{2}}\left[x^2+y^2+\frac{w^2}{4}\right]} \qquad (5)$$

The above equation has been devised on the basis of reflection histories of the form S^{n}D with a reflection sequence given by SSSS…. D. However, it can be shown that all reflection histories which include a single diffuse reflection will result in the same intensity at the receiver. Thus, the total diffuse intensity is given by:

$$I_{Dn} = n\frac{P(1-d)^{n-1}d(2n-1)w}{8\pi^2}\int_0^h\int_{-\frac{l}{2}}^{\frac{l}{2}} \frac{dxdy}{\left[x^2+y^2+\frac{(2n-1)^2 w^2}{4}\right]^{\frac{3}{2}}\left[x^2+y^2+\frac{w^2}{4}\right]} \qquad (6)$$

In principle, from Equations 3 and 6 it should be possible, using an impulse source, to determine **d** for low orders of reflection, by measuring the specular and diffuse intensities and the dimensions of the street configuration. However, the finite duration of a practical impulse means that it will be impossible to separate the two components adequately. Two methods of determining a value of **d** were investigated. In the first, for low orders of reflection, the measured ratio of total intensity (specular plus diffuse) in consecutive orders of reflection, corrected for the effect of additional façade absorption experienced by the higher order of reflection, was compared with theoretical predictions. An alternative method, using higher orders of reflection was also investigated based upon the rapid change in EDT as a function of d (see Figure 1).

5 THE SCALE MODEL

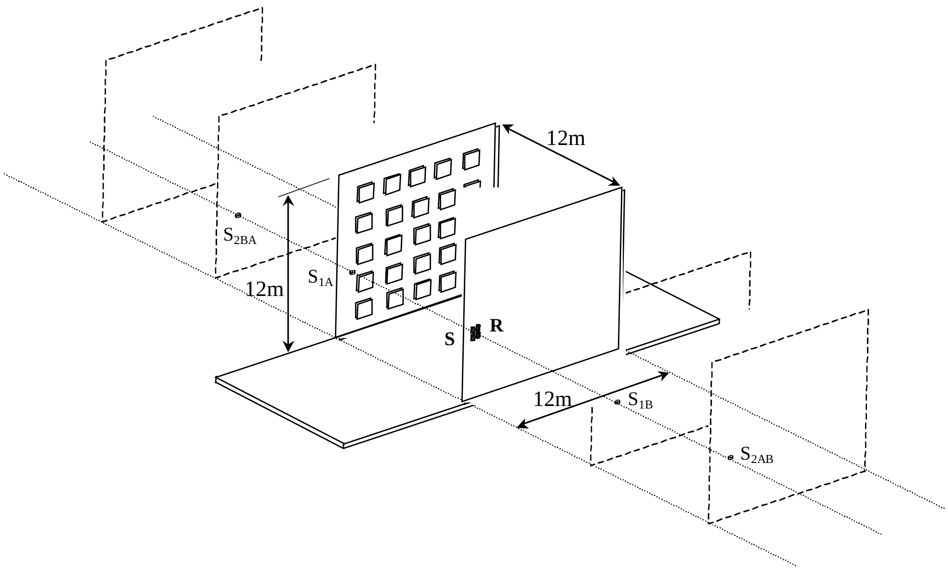

Figure 3: Scale Model Geometry

An idealised street section of 12m-height 12m-width and 12m-length was modeled at a scale factor of 1:10. The model was constructed with varnished MDF sheets. The limited extent of the facades was necessary in order to ensure that the temporal spread of diffuse energy from a particular order of reflection did not extend sufficiently to overlap the sound energy arriving from the following order of reflection.

The degree of diffusion had to be chosen empirically as there is no simple method to predict it from consideration of geometry[9]. The diffusion was created by sticking three different arrangements of varnished MDF blocks, each measuring 10cm*10cm*2.2cm, to the facades. The blocks were arranged in arrays of 3x3, 4x4 and 6x6 for configurations 1, 2 and 3 respectively. Measurements were also made with smooth facades in order that measured EDT's could be normalised relative to specular conditions and the absorption coefficient determined.

A condenser microphone was used as an electrostatic source to ensure uniform directivity. It was located at the centre of the model street immediately next to the measuring microphone. Measurements were made using the MLSSA hardware card which employs the Maximum Length Sequence method (MLS). A feature of the MLSSA system, which was valuable in the context of this experiment, was the ability to introduce a delay in the signal processing procedure. Using this facility, it was possible to "gate out" the direct component at the receiver microphone and thus prevent the direct signal from completely dominating the recorded data.

6 RESULTS

6.1 The Ratio Method

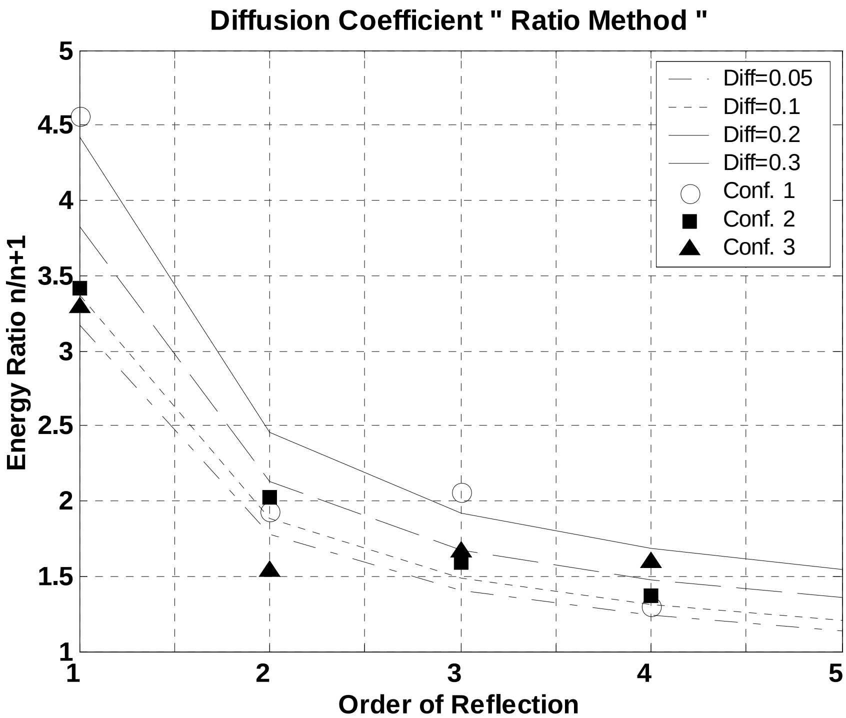

Figure 4: Comparison of measured and predicted ratios of energy in successive orders of reflection.

Figure 4 show a plot of the measured ratios of energy in successive orders of reflection for each configuration and predicted ratios for different values of diffusion coefficient. From this figure it is possible, in principle, to obtain an approximate value of the façade diffusion coefficient. However, although the experimental data for each façade configuration tends to follow the predicted trends there is considerable scatter around the predicted curves. The results for the first ratio display the opposite trend to that expected with the highest value of diffusion coefficient being obtained for configuration 1 and the lowest for configuration 3. The results for configuration 1 are perhaps due to a srong specular component as there were no scattering blocks on that part of the façade closest to the source-receiver position. For ratios corresponding to higher orders of reflection the experimental data tends to settle around theoretical curves corresponding to low values of **d**.

Neglecting the first data point corresponding to configuration 1 and averaging for the remaining data yields approximate values of diffusion coefficient of 0.15, 0.13 and 0.14 for configurations 1, 2 and 3 respectively. This suggests that the diffusion coefficient of a non-smooth building façade with surface irregularities within the range normally experienced is low and not very sensitive to the degree of surface irregularity.

6.3 The Reverberation Time Method

The scale model measurements have been used to obtain reverberation times for smooth street facades and facades with the three degrees of diffusion. A filter based method[10] was used to compensate for excess air absorption. The Schroeder integrated impulse response method was implemented to obtain smooth decay curves. The experimental reverberation time results were plotted along with results calculated using the simple model. The results shown in figure 5 are expressed relative to pure specular reverberation times to avoid the effect of any facade absorption.

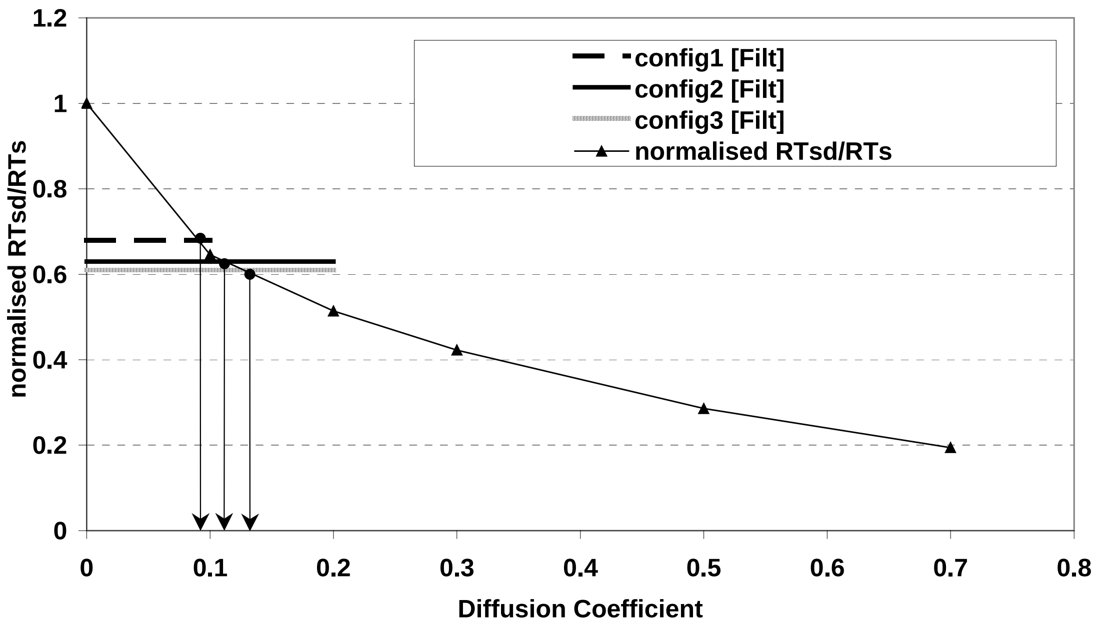

Figure 5: Measured and predicted normalised reverberation times as a function of d.

The horizontal lines on figure 5 show the measured normalised EDT values from which it can be seen that the results of the scale model experiment show a systematic decrease in EDT with the increasing degree of façade irregularity. This corresponds to the trend predicted by the curve obtained from the simple computer model although the range of data is not sufficient to confirm that the trend is towards an asymptotic value.

It is possible to obtain an approximate value of the scattering coefficients from the points of intersection of the horizontal lines with the curve to give values of 0.09, 0.11, and 0.13 for configuration 1, 2, and 3 respectively. These values are similar to those found by the ratio method. Again, it would appear that the diffusion coefficient of a non-smooth building façade with surface irregularities typical of those found in practice is small and not very sensitive to the actual degree of surface irregularity.

7 CONCLUSIONS

In order to enable the effect of higher orders of reflection on sound propagation in streets to be investigated a simplified prediction method has been developed for the case of facades with low diffusion coefficients. This simplified method was used as the basis of an experimental investigation of the magnitude of the diffusion coefficient of three scale model facades having a similar degree of surface irregularity as typical buildings. Measurements of **d** using data relating to low orders of reflection ranged from 0.13 – 0.14, Although these values are of a similar magnitude to those extracted from field measurements, the measured data showed considerable scatter.

Reverberation time measurements on a scale model of a street canyon with three degrees of façade irregularity confirmed the trend, predicted using the simple computer model, namely that the reverberation time tends to decrease with increasing surface irregularity. The value of **d** measured were similar to those obtained from the ratio method, ranging from 0.09 –0.13 with values increasing with the degree of surface irregularity.

Application of both techniques in the field may not be practicable as information relating to the absorption coefficient of real building facades is required for correcting the effect of absorption on later orders of reflection in the ratio method or for normalizing the reverberation time data relative to the case of pure specular reflections for the second method. The value of the façade absorption coefficient normally assumed by researchers modeling urban noise propagation is comparable to in magnitude to that of the diffusion coefficient measured in this work. This means that any attempt to measure **d** will be very sensitive to the value of absorption coefficient employed.

Although the magnitude of façade diffusion coefficient appears to be small, the effect of multiple reflections is to make the diffuse reflection mechanism dominant at higher orders of reflections even with a moderate degree of scattering. It can thus be concluded that far-field urban sound propagation characteristics are governed by the laws of diffuse reflections.

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