THE ROLE OF SPECULAR AND DIFFUSE REFLECTIONS IN URBAN NOISE PROPAGATION

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ABSTRACT

With the increasing number of vehicles and other noise sources in urban areas, the accurate prediction of noise levels inside the city is of growing interest. The complexity of the geometry encountered in city meshes in the propagation environment suggests the need for developing simple propagation models. The role of both specular and diffuse reflections in urban noise propagation and their contribution to the resultant noise levels is still ambiguous. This paper investigates the propagation of the specular and diffuse fields in urban areas. The study looks at the various phenomena [geometrical, physical...etc] that govern the propagation process for specular and diffuse mechanisms. A prediction model has been developed, that assesses the energy transfer between both fields during the spreading process. The study demonstrates the diminishing role of specular reflections as the order of reflections increases.

Keywords – nuisance, outdoor sound propagation, urban noise, radiosity

1. INTRODUCTION

It is important to evaluate the various aspects that might influence the outdoor noise propagation process in urban areas. A variety of computer modelling techniques have been developed, assuming planar facades and simple canyon forms e.g. [1] However, recent work [2-4] has revealed that sound scattering has an important effect when sound waves interact with non-uniform facades. Given the important role that diffuse reflections can play in determining the sound field, it is necessary to understand the behaviour of both the specular and the diffuse sound fields, during the propagation process. The aim of this paper is to assess the role of each field and to outline its importance in determining the impact of the urban form on the resultant sound levels.

2. SOUND PROPAGATION IN STREET CHANNELS

In real streets with rough surfaces the incident energy $E_{incident}$ is redistributed into the diffuse field, E_{Diff}, where its directional distribution is determined by the surface texture , and the specular field, E_{Spec} where reflection takes place according to Fermat's principle. If α denotes the fraction of the energy lost on the surface, and δ the fraction of energy that is reflected diffusely then:

$$E_{Spec} = E_{incident}(1-\alpha)(1-\delta) \qquad (1)$$

$$E_{Diff} = E_{incident}(1-\alpha)\delta \quad (2)$$

Regarding propagation in a street channel, this will result in the second order of reflection having 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. Thus the history of different components of reflection can be identified. The reflection history, $\boldsymbol{R_2}$, for second order reflections could thus be written as:

$$R_2 = R_{ss} + R_{sd} + R_{dd} + R_{ds} \quad (3)$$

Fig [1] illustrates the sequence of reflection histories.

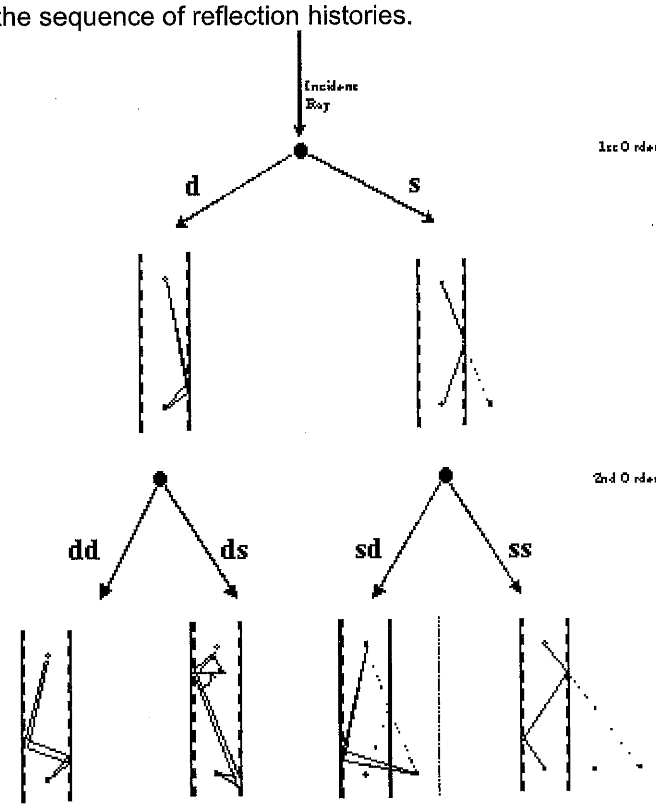


Fig 1: Illustration of reflection histories in an idealised single street channel
(source located at the bottom).

This history could be presented in general for a higher order of reflection, ***n***, as:

(4)

$$R_n = [R_s + R_d]^n$$

Computer models, based on geometrical acoustics [image source] are only able to handle the purely specular reflection history. Other forms of reflection can be simulated using radiant exchange techniques introduced for acoustic models by Moore [5]. In this paper a new method is suggested to handle all reflection combinations, and to separate the pure specular component from all the other combinations.

3. PURE SPECULAR-SPECULAR COMPONENTS

The pure specular component E_{Spec} of the reflection can be calculated using the classical image-source method [1]. It is assumed that for a source in front of a reflecting plane an image-source is created at the same distance behind the plane, and the image will be further reflected in the opposite street façade, creating the various image sources.

For a street with diffusion coefficient δ, and α the fraction of the energy lost on the surface, the energy at the receiver location is achieved by summing up the energy from all image-sources reflected on both boundaries.

$$E(t) = \frac{W}{4\pi} \sum_{B=1}^{2} \sum_{i=1}^{n} \frac{1}{d_{i_B}^2} (1-\delta)^i (1-\alpha)^i \qquad (5)$$

Where d_{iB} is the path length between image source of order i and receiver, $t=d_{iB}/c$, and W is the source power output.
The steady-state Intensity level at the receiver R (R_x, R_y, R_z) is given by:

$$L = 10 \log \sum_{t=0}^{\infty} E(t) / E_{ref} \qquad (6)$$

4. RADIOSITY

The radiosity method was developed to calculate object-to-object diffuse reflections within complex environments. The method provides an accurate representation of diffuse and ambient terms found in image synthesis algorithms and has been used successfully in heat transfer applications. The radiosity method was extended to handle ideal specular reflections, which also means that it can be used to handle specular-mixed and diffuse-mixed reflections. In this work the extended radiosity method has been modified to minimise computational requirements and to allow consideration of high order reflection histories, as will be described in more detail below.

In the conventional radiosity method, all reflecting planes are divided into sub-planes, known as "patches", such that the percentage variation across the patch of incident energy is negligible. The key step in the radiosity method is the computation of configuration and form factors, which encapsulate the geometrical complexity of a given situation. They define the fraction of energy radiated by a source (point or area) to another point or area on a different face. In the case of sound propagation between a source and a receiver in a street channel the following form factors are required:
Point to plane for energy radiated from source and image sources;
Plane to plane for multiple reflections between the sides of street channel;
Plane to point for energy radiated from patches to the receiver.

Details of the procedures used to calculate these form factors can be found in reference [6]. The form factor between two planes **A** and ***B*** is obtained by averaging the form factor from ***B*** to ***A*** at each point of plane ***A***, and then dividing by the area of ***A***, i.e. the form factor between finite surfaces "patches" is defined as the area average.

It has been shown experimentally that the approximation is valid within *5%* for any values of θ_A and θ_B if:

$$\frac{B}{R_{AB}^2} \leq 0.01 \qquad (7)$$

Where ***B*** is the area of patch ***B*** and $\boldsymbol{R_{AB}}$ is the distance between the centes of the two patches.

It is of great importance to divide the planes a minimum number of times to avoid excessive computational requirements. Thus for the optimum subdivision, and to minimise processing speed the following recursive algorithm was developed.
The boundaries of the flanking facades are defined as ***x=0.0*** and ***x=X*** and the initial patch division is defined as ***l (l=1.... Py)*** along the street length and ***m (m=1.... Pz,)***, along the street height and ***L***, and ***H*** are the street length and height respectively.

The stringent criterion for the size of the "patch" is that

$$\frac{(L/P_y)(H/P_z)}{R_{AB}^2} \leq 0.01 \qquad (8)$$

Where $(L/P_y)(H/P_z)$ is the area of the subplane and R_{AB}^2 is the square of the distance between the centres of the receiving and accepting subplanes. This relation is tested for each interaction process; if the division is not enough and the criterion is not satisfied, the patch is subdivided by ***n*** where ***n*** is given by:

$$n = \sqrt{\frac{(L/P_y)(H/P_z)}{R_{AB}^2 * 0.01}} \qquad (9)$$

Where ***n*** is an integer (rounded up from the value of the square root term).

According to this procedure the plane is further divided ***n*** number of times and adjacent planes may be divided into a different number of patches as illustrated in Figure 2.

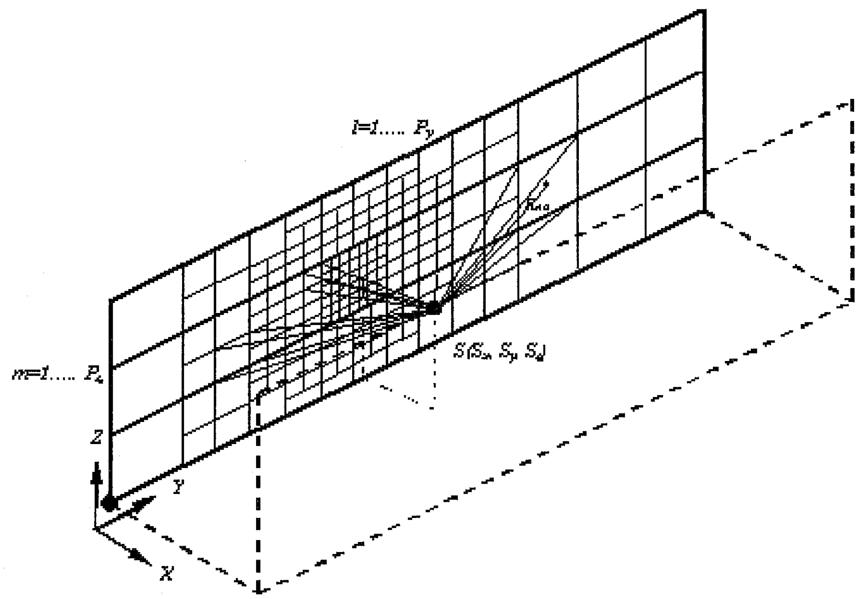


Fig 2: Isometric view of a single street channel showing the geometry of the patch division for a source point positioned at S (S_x, S_y, S_z).

The basic radiosity method is only able to handle pure diffuse reflection components although it has been extended to handle ideal specular and mixed reflection. However it relies on creating the complete subplane and network of patches as images with the high orders of reflections handled between the image geometry mesh and the original space under investigation. The extended radiosity method if applied to handle cases of outdoor noise propagation where the geometry is more complex, will result in unfeasible computational demands. Thus the extended radiosity method has been modified in this study to enable it to handle all possible reflection histories. The technique developed and described in this paper reduces the memory that the process requires by compressing the memory allocation needed during the running phase and by minimising the calculations required for the specular-mixed, diffuse-mixed reflection components.

5. DIFFUSE AND MIXED SPECULAR-DIFFUSE REFLECTIONS

Figure 1 illustrates the various configurations of interactions up to the second order of reflection. The stored image-source data is used to model the specular-mixed components. The program works out the purely specular components of the sound propagation process, according to the image-source model, to the desired order of reflection and calculates the energy content of each source image according to the diffusive coefficient (***1- δ***); the rest of the energy is transferred into the first order diffusive interaction. The diffusive energy is assigned to each patch element of the face using form factors and the radiosity exchange mechanism.

To model the diffuse component, the program establishes the interactions using the radiant exchange method up to the desired order of reflections; the energy lost in each interchange is a fraction ***δ*** of the energy, which the patch preserves. However (***1 - δ***) of the energy on the patch will be reflected specularly, according to Fermat's principle. The specular paths are embedded inside the diffuse propagation calculation procedure. Thus the program works out the cases where specular propagation rules are satisfied and then allows the total energy content of the patch to be released, this is modelled as will be described below. This process will allocate all the mixed specular components of the reflection for any order of reflection. This procedure will reduce the memory requirements. The reflections have all to be stored till the end to calculate time histories.

5.1 DIFFUSE-ENERGY TRANSFER PROCESS

Sound energy of the impulse source is first assigned to the patches and these in turn can be regarded as sound sources radiating further energy to patches located on the other façade. The sound energy transfer from source to patch will involve the point to patch configuration factor. The patches are all assigned first order energy and the following diffuse interactions will be handled using patch-to-patch form factor calculations. This is the way the pure diffuse-diffuse interactions are handled in the basic radiosity method. The energy assigned to patch ***j*** is given by:

$$E_j(t) = \sum_{k=1}^{K} E_k F_{jk} \qquad (10)$$

Where E_k is the sound energy per unit area per ***s*** on patch k, F_{jk} is the form factor relating radiation from patch k and ***K*** is the total number of patches.

5.2 SPECULAR-DIFFUSE REFLECTIONS

Specular-diffuse reflections have reflection histories consisting of an sequence of specular reflections followed by diffuse reflections and are thus of the form sssd etc. Specular-diffuse reflection thus occur when the reflection history is for reflection orders ***1...i-1*** specular and ***i*** diffuse. This is handled by regarding the ***m-1*** order image-source as a source radiating first order patch energy to the opposite patch boundary, the interaction is taken further between the patches for ***n- (m-1)*** times.

If E_{i-1} is the energy content of the image source located at S_{m-1} after ***m-1*** successive specular reflections, the energy is assigned to the opposite face by a point to patch configuration factor, thus if $S_x>0.0$ then boundary B_1 is handled, if $S_x<0.0$ boundary B_2 is processed.

Thus the energy reaching element patch ***j*** due to the contribution from image source S_{m-1} is given by:

$$E_j(t) = F_{ik} E_{m-1} \qquad (11)$$

Where F_{ik} is the point to patch form factor relating to radiation from the image source to patch j and

$$t = \frac{R_{ij}}{c} \qquad (12)$$

As stated above, the energy interactions are taken further for ***n-(m-1)*** to achieve the desired order of interactions.

5.3 DIFFUSE-SPECULAR REFLECTIONS

Diffuse-specular reflections take place when energy that has been diffusely reflected from the previous surface undergoes specular reflection from the next surface. Diffuse-specular reflections thus take place when the reflection history is for reflection order ***i-1*** diffuse and order ***i*** specular. Korany et al [7] dealt with the diffuse-specular component, by implementing the extended radiosity method where all the geometry of sub planes and patches are created as images for the order of reflection examined. The specular reflections are established through the energy exchange between the image-patches and the original patch geometry. This process, for conditions were the geometry will become problematically complicated, such the case of outdoor situations will become unfeasible. Thus the diffuse-specular reflection is handled differently in this study, to the demands on memory during the running phase of the program.
The standard radiosity process which deals with diffusive interactions actually considers all the possible paths that the energy- between patches might undergo and thus it includes the paths which specular reflections would follow i.e. according to Fermat's principle, where the reflection takes the path with the shortest time delay as illustrated in Figure 3. Therefore, a function $H_{(\theta1,\varphi1,\theta2,\varphi2)}$ is introduced, to test for the specular reflection criterion to be satisfied as follows:

$$H_{(\theta_1,\varphi_1,\theta_2,\varphi_2)} = \begin{Bmatrix} 0 \rightarrow if..specular..reflection \\ 1 \rightarrow if..diffuse..reflection \end{Bmatrix} \quad (13)$$

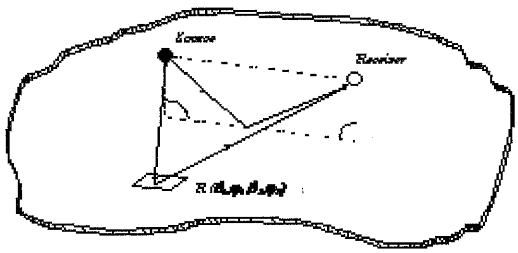


Fig 3: Reflection paths: specular according to Fermat's principle, and the scattered reflection $R_{(\theta1,\varphi1,\theta2,\varphi2)}$ where the amplitude is a function of the incident angles and the reflection angles

This process will account for the diffuse-diffuse and diffuse-specular interaction, as these combinations of reflections could be present for the same path and time delay. In this case the total energy of the radiating patch is released having $H_{(\theta1,\varphi1,\theta2,\varphi2)}=0$.
Introducing the function $H_{(\theta1,\varphi1,\theta2,\varphi2)}$ has the benefit of handling a reflection order of ***i=1.....:*** for the diffuse-specular combinations, as it recognises and tests all the reflection paths across all the angular range for Fermat's principle criterion to be satisfied. This will include parts of higher order of reflections for the diffuse-specular components, which the extended radiosity method will not be able to handle.

By considering all order of patch sources as well as the direct energy transport from the source to the receiver, the impulse response at receiver position ***R***, for reflections of order ***i=1...n*** can be given by the summation of the pure specular and the diffuse energy.

$$L(t) = 10\log[\,E_d(t) + \sum_{i=1}^{i=n} E_s(t) + E_{d,s}(t)] \tag{14}$$

Where $\boldsymbol{E_d(t)}$ is the direct energy, $\boldsymbol{E_s(t)}$ the pure specular, and $\boldsymbol{E_{d,s}(t)}$ the diffuse-mixed specular-mixed energy.

6. SIMULATION OF SOUND PROPAGATION IN A STREET

Using the above approach, the behaviour of specular and diffuse energy as a function of the order of reflection has been investigated. For convenience, the calculations have been performed on idealised street canyons in which the building were continuous along the street length with constant height. Both facades were assumed to have constant diffusion coefficient and for both surfaces $\boldsymbol{\alpha}$ was assumed to be of zero magnitude as this will have no effect on the energy transfer between the specular and the diffuse sound fields.
Unlike other work this investigation is concerned with the separation of the specular and the diffuse energy as the order of reflection increases. Thus, a high order of calculation is needed. The patch division process described out earlier serves along with the modified extended radiosity for the diffuse-specular parts of reflections to in reduce the processing time. Thus it was possible to run the model to include fifth order reflections with reasonable processing time.
The model was run for a street geometry, where the street dimensions were length L_S=*100m*, width W_S=*20m*, and height of H_S=*20m*. The source was located at *S (10, 27, 2)* with *0.5W* power output, and the receiver at *R (10, 72, 2)* resulting in a source receiver separation of *45m*. The program established the patch division according to the source location, and the form factors were calculated to distribute the energy to the first-order patch sources and the program then processed the subsequent energy transfer. The energy content of both fields [diffuse and specular] was separated for each order of reflection to investigate whether the diffuse or the specular field dominates with increasing order. The energy-time series for each order of reflection for the above configuration is presented in Figure 4.

The energy responses shown in Figure 4 illustrate the effect of diffuse reflections on extending the echogram in time. The time series is extended for each order of reflection, according to the source-receiver positions as given by:

$$T_i = \frac{(i+1)^i * \sqrt{W_s^2 + L_s^2 + H_s^2}}{c}\ \text{sec} \tag{15}$$

Where $\boldsymbol{i}$ is the order of reflection, $\boldsymbol{W_S}$, $\boldsymbol{L_S}$, and $\boldsymbol{H_S}$ are street width length and height respectively.
To assess the role of each sound propagation field, namely the specular and diffuse, with the increasing order of reflection. For each order of reflection, the amount of energy reflected for the specular and diffuse field relative to the total amount of energy in was plotted. Thus for specular and diffuse:

$$Specular = \frac{E_{s,i}}{E_{s,i} + E_{d,s,i}} \tag{16}$$

$$Diffuse = \frac{E_{d,s,i}}{E_{s,i} + E_{d,s,i}} \qquad (17)$$

The plot showing the effect of the increasing order of reflection is shown in Figure 5. It can be seen from Figure 5 that the specular energy content diminishes with increasing reflection order until the diffuse field dominates completely.

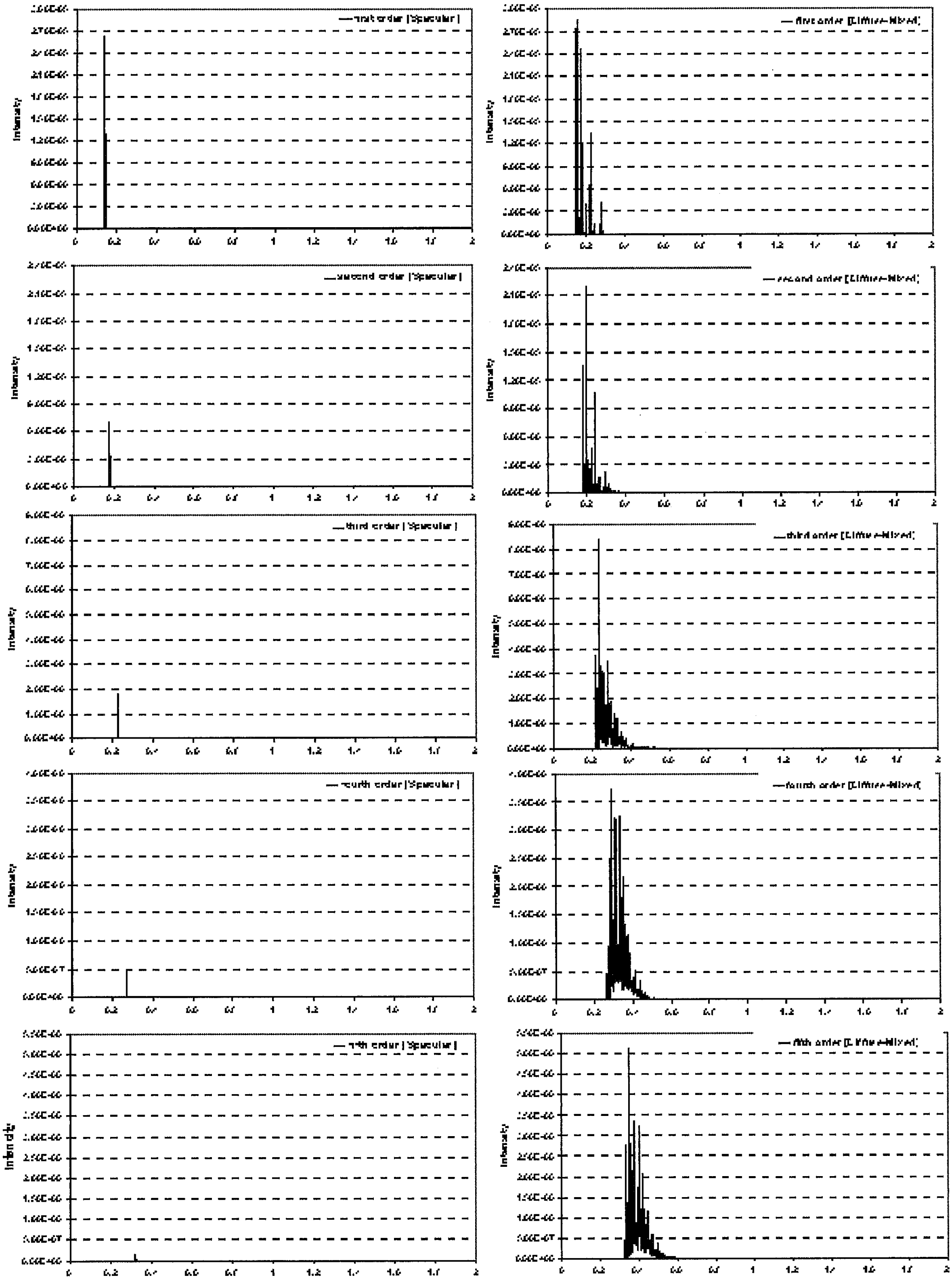


Fig 4: Energy responses, specular on the left and diffuse on the right, separated according to the order of reflection starting above at the first order down to the fifth.

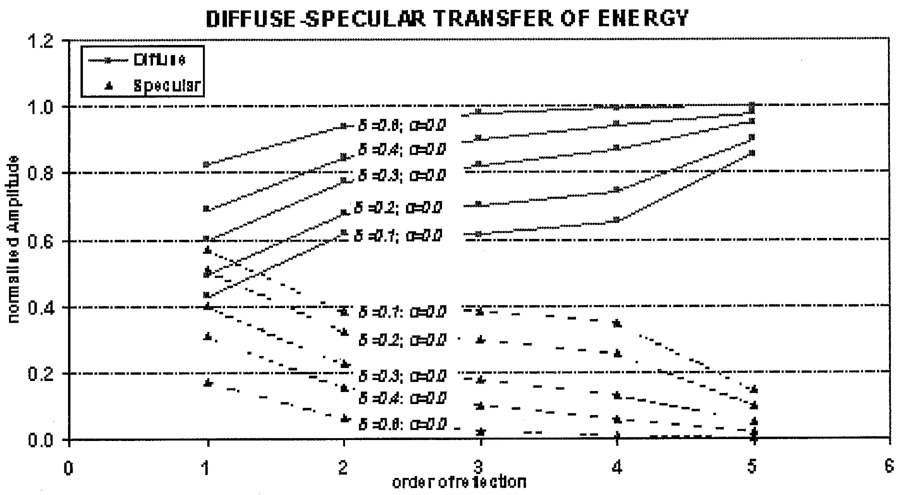
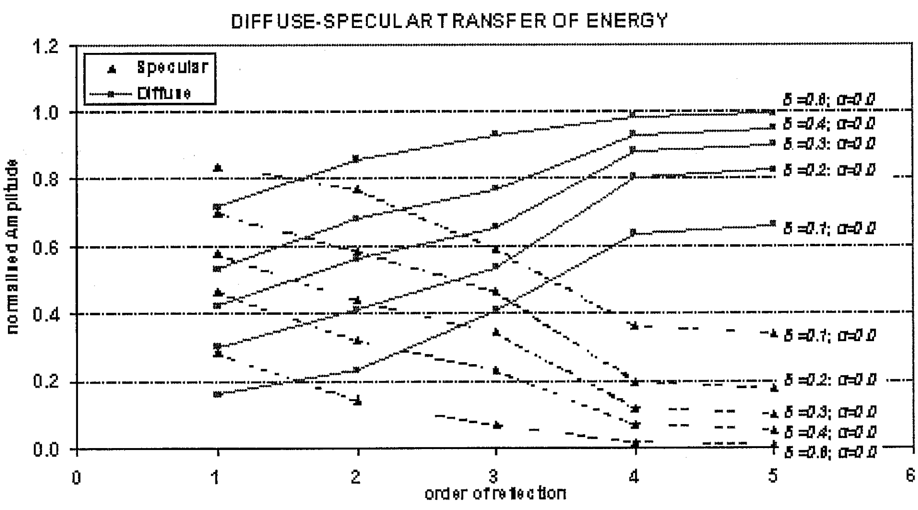


Fig 5 Diffuse-specular transfer of energy for different diffusion coefficients for
street length L_S=100m, width W_S=20m, and height of H_S=20m. S (10, 27, 2 with 0.5W power output, and the receiver at R (10, 72, 2).



Another set of plots were obtained for a street of dimensions length L_S=*50m*, width W_S=*20m*, and height of H_S=*20m*. *S (10, 2.5, 2)* with 0.5W power output, and the receiver at *R (10, 47.5, 2)*. The source-receiver separation distance was kept the same at a distance of 45m. The data obtained is shown in Figure 6.

Fig 6: Diffuse-specular transfer of energy for different diffusion coefficients for street length L_S=50m, width W_S=20m, and height of H_S=20m. S (10, 2.5, 2)
with 0.5W power output, and the receiver at R (10, 47.5, 2).

A general finding is that for a diffusive coefficient of *δ=0.2*, for almost all the configurations examined the diffuse energy content in the reflection reaches a value of about *80%* of the total energy after just four reflection. Urban noise is determined by the addition of noise from remote sources, thus the propagation parameters relate to those for high orders of reflection, where the diffusive mechanism becomes dominant after a few orders of reflection. This illustrates the role the diffuse energy plays in the propagation and spreading of sound outdoors since the effective noise sources in the urban environment are located at remote positions relative to the residential plots. With higher values of diffusion coefficient the transfer of energy from the specular to the diffuse domain is much faster. This analysis and the fact that the street facades are generally not smooth homogeneous planes, suggests that a significant part of the propagation process is determined by the diffusive reflection mechanism, and that a model based upon diffuse reflections might be most appropriate.
Since the purely specular reflection process is restricted by very rigid rules, other factors may affect its propagation process. In general most built-up area morphologies follow an interchanging space pattern, thus most of the streets in the city are rarely continuous non-interrupted streets. The most common type of street is street with gaps, various types of intersection, and even more complicated urban configurations. These will all act to limit the propagation of sound by specular reflections, since with the above geometry not all image-sources will be seen by the receiver position and thus some of the specular energy might be cut-off.

7. CONCLUSIONS

A computer model has been developed, to handle all the possible reflection combinations encountered in noise propagation in a street channel. The pure specular field has been accounted for by implementing the classical image-source theory, and for all the other components a radiant exchange techniques has been developed. The processing time has been minimised by introducing a reduced patch division technique, and a new modified extended radiosity method to minimise the computing requirements during the running phase of the program.
The energy content of each propagation phase, namely the specular and diffuse, has been separated and its fraction to the total energy amount in each reflection has been analysed. The data for different diffusion coefficient revealed the diminishing role of the specular field as the order of reflection increases. For even a low diffusion coefficient of *δ=0.2*, at the fourth order of reflection about 80% of the reflection energy is transferred into the diffuse mode. As the urban morphology is not always composed of idealised continuous streets, but of other configurations of interrupted facades and scattered building blocks etc., which reduces the role of the specular field more in obstructing image-sources which are hidden from the receiver due to the geometrical configuration.

The above factors suggest that the diffusive field is the dominant for the outdoor sound propagation conditions and that a model developed based upon diffusive theories might form a good approach to the development of a fast effective tool for predicting outdoor sound propagation in urban areas.

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