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THE PROPAGATION OF NOISE THROUGH THE URBAN FABRIC

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1. INTRODUCTION

The propagation of noise through the urban fabric has been the subject of much research. However, most of this research has been concerned with the propagation characteristics of single streets. See for example, WIENER, MALME, and GOGOS [1,2], DELANY [3], WIENER et al, SCHATTER [4], DAVIES [5], STEENACKERS, MYNCKE, and COPS [6], RADWAN and OLDHAM [7] and KINNEY [8]. Of increasing interest is the diffusion of sound from a multitude of noise sources, which contribute to the general noise level in urban situations. Noise diffusion inside the urban fabric has been investigated on a 1:50 scale model by PICAUT and SIMON [9]. The results presented were used to validate a 3D diffusion theoretical model [10] originally used to predict sound fields in rooms with diffusely reflecting boundaries which was developed to study outdoor noise propagation.

In this paper a computer model is described which has been designed as an investigative tool for the study of noise propagation through the urban fabric. The model builds upon the work of KANG [11] who used a geometrical patch division approach to build a computer model of sound propagation down a street channel based upon the principle of radiosity. Kang demonstrated that provided the street width was smaller than the height of the buildings there was little difference between propagation characteristics calculated assuming specular or diffuse reflections. In the model described in this paper it is assumed that the building facade irregularities result in diffuse reflections.

2. RADIOSITY

In an array of building blocks as shown in figure [2.1] as presented in this model, all the buildings are placed in perpendicular streets for simplicity. Energy is assigned from the source to all faces, then the energy content of each face is re-radiated to all the other faces, till this process reaches the equilibrium, energy from each face to the reception points is then summed up.

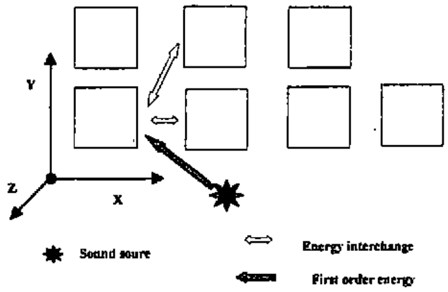


Fig 2.1:
First order energy assignment, and interchange of energy between faces.

The key step in the radiosity algorithm is the ***configuration factor*** (form factor) computation. The ***configuration factor*** is the quantity that encapsulates the geometrical complexity. It is the percentage of energy radiated by a source point (or patch) to a patch on a different face. Thus, considering the re-radiating of energy, a double integral must be performed to calculate the factor for two faces. This a factor thus has limits of

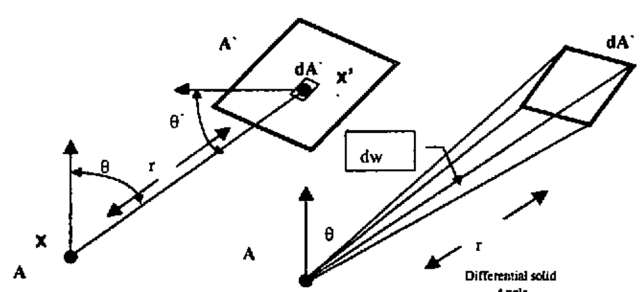
0.0<=C<=1

The ***configuration factor*** between differential area [dA`] and a point is given by

$$dF_{dA \longrightarrow dA`} = \frac{\cos\theta}{\pi} dw` = \frac{\cos\theta \cos\theta`}{\pi r^2} dA` \qquad [2.1]$$

Where [**r**] is the distance between positions [**x**`] and [**x**] and [θ] is the angle between the normal to the surface work plane at [**x**] and the direction from [**x**`] to [**x**], [θ`] is the angle between the normal to the surface at [**x**`] and the direction from [**x**`] to [**x**], and [**dw**`] is the differential solid angle subtended by [**dA**`] from [**A**]. The geometry of these terms is shown in fig [2.2].

Fig: 2.2:
Configuration factor geometry



The fraction of energy leaving [**A**] that arrives at [**dA**`] is proportional to the solid angle [**dw**`] subtended by [**dA**`] as viewed from [**A**]. The ***configuration factor*** thus depends inversely on the square of the distance and on the cosine of the angle [θ`]. The ***configuration factor*** from a face [$\mathbf{A_J}$] to [$\mathbf{A_i}$] is obtained by averaging the form factor from [$\mathbf{A_J}$] to [$\mathbf{A_i}$] at each point of [$\mathbf{A_J}$], i.e. we take the integral of [$\mathbf{F}_{dj\,i}$] over all the patch [j] and divide by the area of [$\mathbf{A_J}$].

$$F_{ji} = \frac{1}{A_j} \int_{A_j} \int_{A_i} \frac{\cos\theta_i \cos\theta_j}{\pi r^2} dA_i dA_j \qquad [2.2]$$

$$F_{ji} = \frac{1}{A_j} \int_{A_j} \int_{A_i} \frac{\cos\theta_i \cos\theta_j}{\pi r^2} \mathrm{H}_{ij}\, dA_i dA_j \qquad [2.3]$$

In the presence of potentially occluding objects [$\mathbf{F}_{dj\,i}$] must be tested for visibility and left out of the integral if occluded, by inventing an operator [$\mathbf{H}_{i\,j}$] which is unity if [$\mathbf{dA}_j$] is visible from [$\mathbf{dA}_i$], or zero otherwise.

In general the double area integral has proved difficult to solve analytically, and numerical methods are implemented in calculating the ***configuration factor.*** This is equivalent to projecting the receiving patch into a unit hemisphere centred about the radiating patch, and further projecting this projection down to the circle base of the hemisphere and dividing it by the area of this base circle. This is called the *hemicube method* [12]. The ray-tracing method is essentially just the opposite of this procedure. ***Configuration factors*** [$\mathbf{F}_{j\,di}$] from a finite area to a differential area are computed [13]. Radiosity computation is intense and difficult because, in a geometrically complex scene, the movement of energy is also complex. It is thus one of the most computationally expensive methods, used in image syntheses and is just now becoming feasible with the advances in processing speeds. However, in the case of outdoor urban propagation the geometrical parameters are more complex than other cases, thus a simplified approach is desirable. A new pseudo radiosity method is described in the next section, based on solid angle calculations.

3. THE PSEUDO RADIOSITY APPROACH

Implementing the law of conservation of energy, the ratio of energy radiating through the solid angles enclosed by the radiation point and the face, to the total energy of the source, should lie in accord with the ***configuration factor*** values.

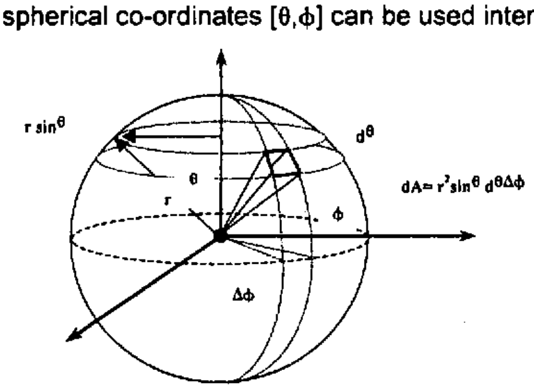
3.1 SOLID ANGLE CALCULATIONS:

A direction is indicated by a vector [**w**]. Since this is a unit vector, it can be represented by a single point on the surface of a sphere. The positions on the sphere in turn can be presented by two angles.

[θ] =The number of degrees from the north pole or zenith.

[ϕ] =The number of degrees about the equator or azimuth.

Thus directions [**w**] and spherical co-ordinates [θ,ϕ] can be used interchangeable.



An advantage of thinking of directions as points on a sphere comes when considering differential distribution of directions. A differential distribution of directions can be represented by a small region on the unit sphere. The area of a small differential surface element on a sphere of radius [r] is.

$$dA = (rd\theta)(r\sin\theta d\phi) = r^2 \sin\theta d\theta d\phi \qquad [3.1.1]$$

Here [**r dθ**] is the length of the longitudinal arc generated as [θ] goes to [θ+**dθ**]. Similarly [**r dφ**] is the length of the latitudinal arc generated as [φ] goes to [φ+**dφ**]. The product of these two lengths is the differential area of that patch on the sphere.
The differential solid angle, indicated as [**d**], is then

$$dw = \frac{dA}{r^2} = \sin\theta d\theta d\phi \qquad [3.1.2]$$

It is very convenient to think of differential solid angle in terms of a vector, [**dw**]. The direction of [**w**] is in the direction of the point on the sphere, and the length of [**dw**] is equal to the size of the differential solid angle in that direction.
Consider a point source **S** at (**Xs, Ys, Zs**), the first order energy assigned to the face can be calculated using the following equation, assuming hemispherical propagation.

$$E = \frac{W}{2\pi}\sin\theta\Delta\theta\Delta\varphi \qquad [3.1.3]$$

Where [**E**] is the energy assigned to the selected face, [**r**] is the distance from the vertex of the face to the source, and θ, Δθ, Δφ [see Fig. 3.1.1] are the angles determining the mutual spatial location of the face with reference to the source, which are calculated by

$$\Delta\theta = \arctan\frac{X_{UR} - X_S}{Y_{UR} - Y_S} + \arctan\frac{X_{UL} - X_S}{Y_{UL} - Y_S} \qquad [3.1.4]$$

$$\theta = \arctan\frac{Y_{UL} - Y_S}{Z_{UL} - Z_S} \qquad [3.1.5]$$

$$\Delta\varphi = \arctan\frac{Z_{UL} - Z_S}{Y_{UL} - Y_S} + \arctan\frac{Z_{LL} - Z_S}{Y_{LL} - Y_S} \qquad [3.1.6]$$

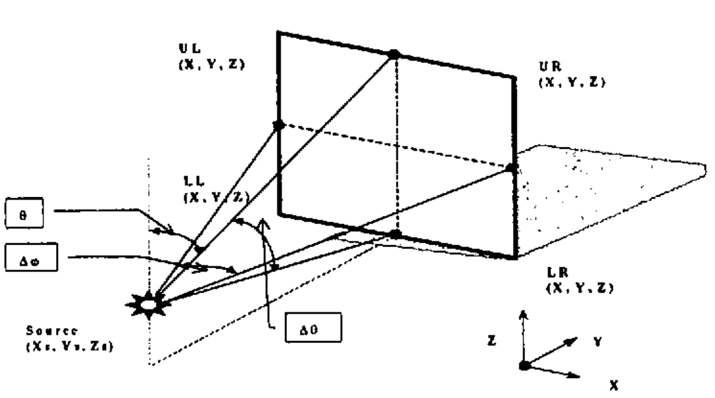


Fig. 3.1.1:
Three-dimensional geometry of an idealised point to face solid angle, showing an example of energy assignment.

In the case of energy re-radiating from a face to others, a point source is assumed to be assigned the energy content of the radiating face, placed at its centre, thus simplifying the faces disproportionality, which is considered in the ***configuration factor*** calculations.
The differential ***configuration factor*** is a smooth function, in the sense that the cosines and $1/r^2$ are continuous in all derivatives as [**dA`**] moves about over the domain, hence the form factor transformation should fit the ***solid angle*** transformation of energy. The only deviation between both results will be because of the change of the ***configuration factor*** fraction with the proportion of the two geometrical elements when performing the element to element double area integral.

$$F_{A \xrightarrow{A'} A'} = \frac{1}{A}\int_A \int_{A'} \frac{\cos\theta \cos\theta'}{\pi r^2} dA dA' \qquad [3.1.7]$$

On the other hand the ***solid angle*** is considering the face as a point source and disregarding the proportionality factor of the faces. The effect of this can be seen by comparing the results of both methods for different building heights (different Proportions) as seen in [see Fig. 3.1.2] calculations are performed for a fixed building height for different face length/grid length (offset distances for the blocks) for two orthogonally positioned faces. There is a moving turning point (when the face is a full square) with changing proportionality for the divergence of the results between both algorithms. The difference between the results is quite promising, and suggests that replacing the ***configuration factor*** algorithm with the ***solid angle*** can be done without encountering great error thus facilitating the approach.
Thus the solid angle algorithm can be developed, to predict the sound propagation parameters inside this multicell zone.

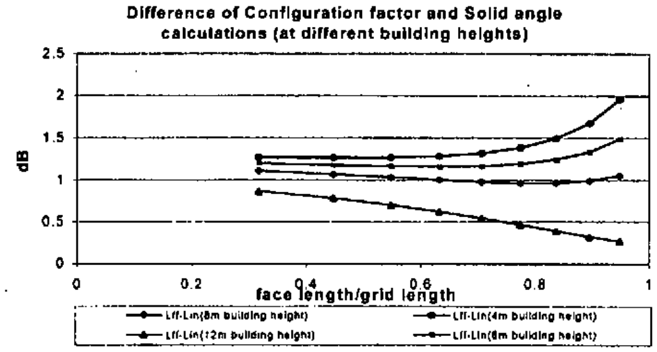


Fig.3.1.2:
Divergence of configuration Factor calculations and solid angle

4. THE COMPUTER MODEL

4.1 GEOMETRICAL ENVIRONMENT

In terms of the total plot area length and width parameters, the computer model works out the Cartesian co-ordinate system, having all streets and building faces perpendicular to each other. Crooked and different angular street intersections, tapering etc. are ignored in this stage of the study, for simplicity and for the sake of computing time.
All the edge points of the buildings are expressed in terms of Cartesian co-ordinate variables in the [**X, Y, and Z**] direction.
In order to calculate the energy assigned to each face, or the energy exchange between the faces and finally the summation at the field points, it is essential to determine the relationship between the station point whether it is considered to be a radiating point source or an accepting field point.
The following two variables are employed to define the location of a particular building block inside the whole building array.

[j] = Number of blocks row
[i] = Number of block inside the row (column rank)
The sequence of assigning the position number variables begins, from the origin where **[X=0.0, Y=0.0, Z=0.0]**, then the column arranging numbers increase in the direction of the X-axis, and the row arranging numbers increases in the direction of the Y-axis, as shown in the fig [4.1.1]. In all building blocks each face then is assigned a rank number in an anticlockwise direction.

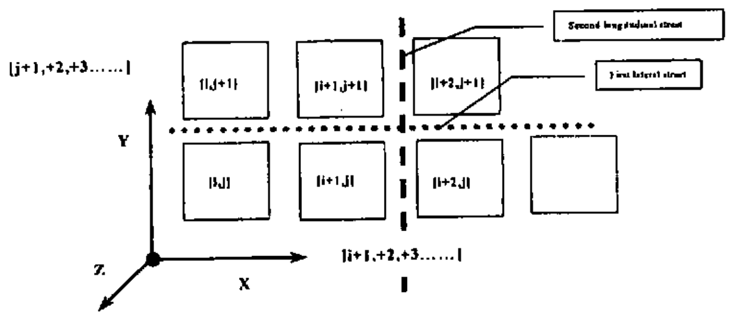


Fig 4.1.1:
The mutual arranging numbers between the blocks, used to decide upon which block to execute in the calculations

The streets are assigned ranks also increasing from the origin, and are split into lateral streets and longitudinal streets as shown in Fig [4.1.1].

4.2 SEQUENCE OF EXECUTION:

After the geometrical mesh is constructed, the calculation procedures begin to assign energy from the source to the different facades of each building block according to a sequence of execution. The first block in the first row is first executed then all the others in the column sequence till the first row is completed. The program then shifts to the first block in the second row and so on till the second row all executes, the sequence is as follows, **[(i, j), (i+1,j), (i+2,j)...(i+N, j), ...(i,j+1), (i+1,j+1), ...(i+N,j+M)]**, where **[N=total number of columns]**, and **[M=total number of rows]**, with this sequence of execution all the blocks are called and processed one by one. When each building block is called the calculations proceeded in the mathematical model handle in particular one face only, whether in the stage of first order energy assignment or in the stage of energy interchange and summation at a field point. Thus each face according to its arrangement rank number in the block is called according to the following sequence **[F1, F2, F3, F4]**.

Whether the street is a longitudinal street or a lateral street, the program then divides the streets section into **[N_{FP}-1]** sections, where [N_{FP}] is the number of field point specified by the user. The field points are then arranged in a sequence. The procedure of summing up the energy starts with the first point located in the first longitudinal street, then the second and so on till the levels for all points in the first street are calculated. The second street is then called and executed and in the same way, the procedure is completed for the lateral streets, where the sequence is as follows **[(k, m), (k+1,m), (k+2,m)...(k+ N_{FP}-1, m), ...(k, m+1), (k+1,m+1)...(k +N_{FP}-1, LS)]**, where **[LS]** is the number of longitudinal streets, **[N_{FP}]** is the number of field points printed by the user, **[k]** is a sequential variable for the number of field points, **[m]** for the number of streets.

In the stage of energy summation the first field point is selected, then all the blocks are executed to sum up its faces energy content taking into account the occlusion effect which will be described in the next section.

For the process of energy interchange between all the faces, the first block is called then beginning with the face sequence, mentioned earlier **[F1, F2, F3, F4]**, then all the blocks with all face sequences are assigned energy from the executed face, and the process mains till all faces are executed and the energy is interchanged between all the faces.

4.3 ENERGY ASSIGNMENT

With the geometrical environment constructed as described, the next step is to distribute the sound energy of the source to the faces, which are actually visible to the face. This means that occlusion is to be taken into account, which will be described, in the following part. To present the calculations of the first order energy distribution, we have first to consider that the model is built up of two identical Cartesian co-ordinate systems, showing the various variables of the model. The first co-ordinate system is the description for the nodes of each face of the building and the second co-ordinate system is to be calculated according to the silhouette around the areas in view of the source as seen in fig [4.3.1].
The main aim behind creating two co-ordinate systems, is the fact that the control procedures employed in the computer model need the original co-ordinate system in all the processing stages of the program.

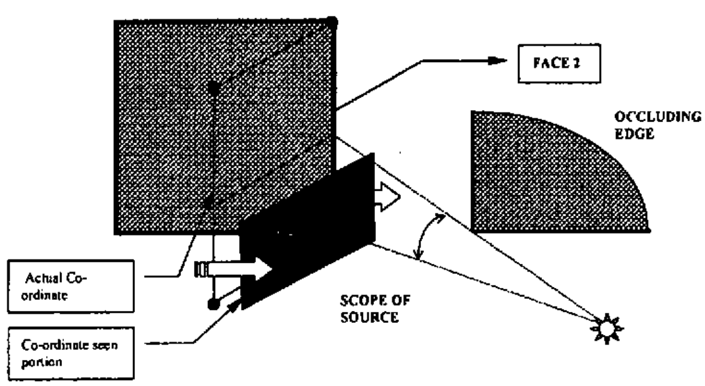


Fig 4.3.1: Actual co-ordinate system and, and co-ordinate system portions seen from the scope of the source [not occluded].

The occlusion procedures calculates the co-ordinates of the visible portion, from a source, whether it is a point radiating or a face interchanging energy with others. Before moving to another selected source radiating energy, this co-ordinate system is reset and given the same standard values of the co-ordinates of the actual system. This means that this auxiliary co-ordinate system is modified each time a radiating source is selected to be set to the values according to the occluded parts, from this particular position of the source.
After the auxiliary co-ordinate system is created, each block is invoked to calculate the energy assigned to the faces, according to the sequence described previously.

5. RESULTS

This section describes the results obtained from the program employed on a [100m*100m] site, planned to include [3] lateral streets and [3] longitudinal streets, with [60%] building density and [6m], building height and a [0.5 w] power output for the source. The geometry is as shown in fig [5.1]. Results are extracted at two positions [100,0,2], and [100,50,2] in fig [5.2].

The decay curves are represented as shown in the charts for each particular position. At position [100,0,2] the predicted values for the streets that are at more remote positions from the source lie behing the nearer streets, note that the SPL is enhanced when the field points lie inside the

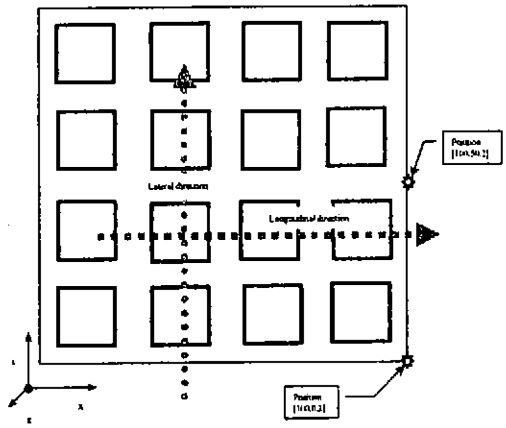


Fig 5.1
Geometry applied to the computer model site [100m*100m], building density [60%], building height [6m]

intersections of the streets, this is because of the fact that almost all the energy assigned from this position for all the affecting faces is almost indirect energy, thus the field points recieve more sound energy when they recieve more contribution from many faces.

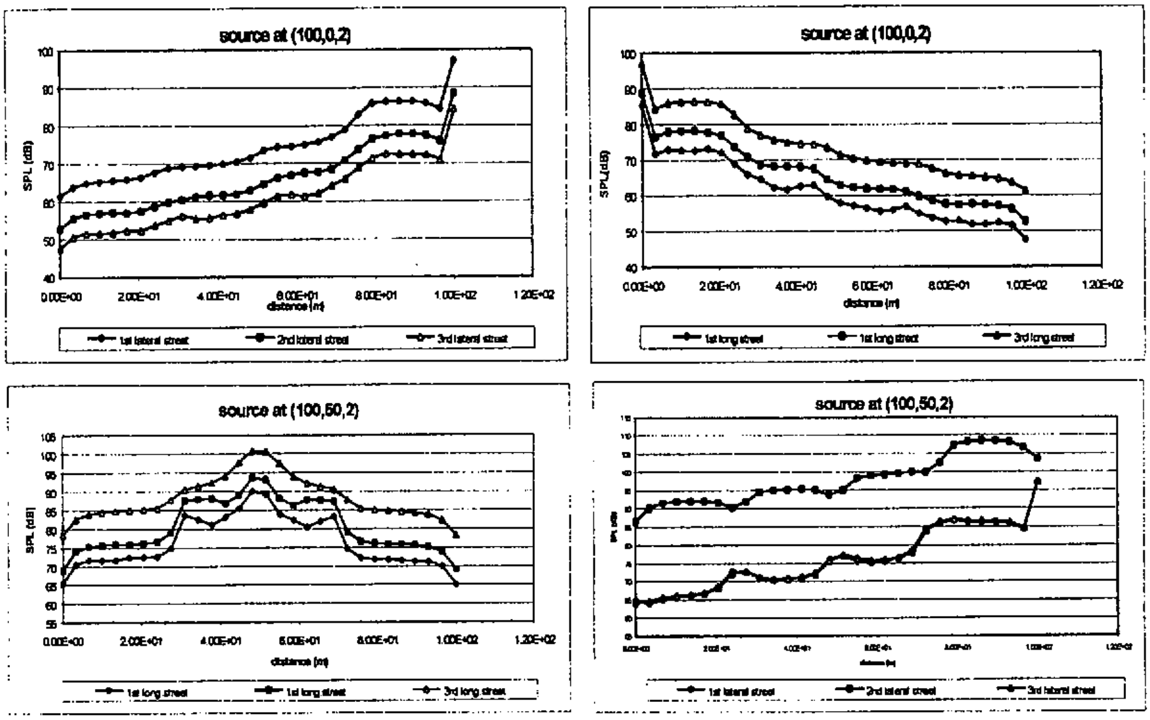


Fig 5.2
SPL predictions at different source positions, at [100,50,2] and [100,0,2]

This is in contradiction with the 2^{nd} lateral street at position [100,50,2]. The source at this positions lies exactly at the end of the street, in this case all the faces at this street recieve direct energy from the source which enhances the energy content of the faces lying in this street. For the faces in the 1st and 3rd lateral street at [100,50,2] they get all their energy content through other faces (indirect), thus sound level is enhanced at the field points which are in sight of the longitudinal streets.

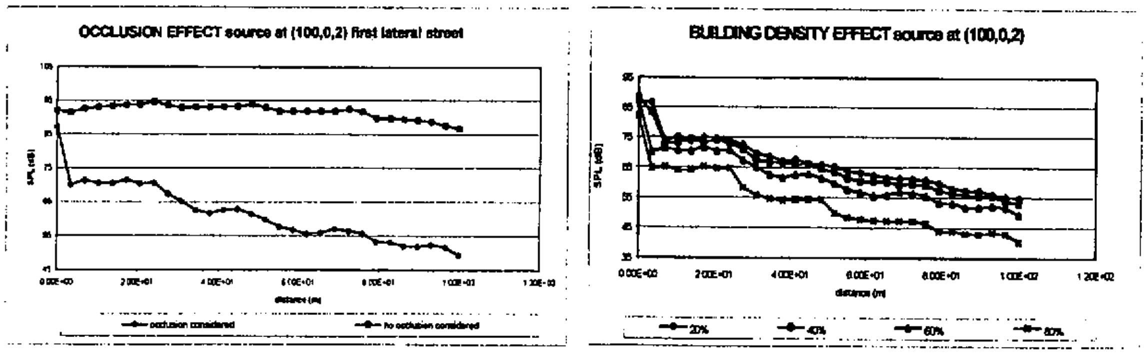


Fig 5.2
SPL predictions at different building densities, at [20%, 40%, 60%, and 80%], and with occlusion and without occlusion

At position [100,0,2] for the same parameters, the effect of changing the building density has been investigated for [20%, 40%, 60% and 80%]. From fig [5.3] it is apparent that increasing the building density reduces the SPL predictions, as the building density increases the occlusion effect of the buildings to each other increases. The decay slope increases also as well with increasing building density. This is more apparent in the curve showing the predicted results with occlusion and without occlusion for the same parameters and [60%] building density.

6. DISCUSSION

Sound propagation through the urban texture has been investigated, assuming that building faces produce perfect diffusion. Diffusion is introduced to take account of the complex nature of sound propagation through the urban fabric, such as multiple reflection and diffraction. A radiosity theoretical method has been described based on the rules of energy conservation. The geometrical complexity of the urban scene, and the intense nature of the radiosity calculations, suggests the need to device some simple investigative tool. Making use of the energy conservation rules, the energy exchange between the faces are calculated by means of the solid angle ratios assuming hemispherical propagation for the source so that the energy exchange between faces is replaced by point sources located at the centre of each face. The results obtained and compared with these from applying the radiosity theory proved to be comparable. The model has been developed using Fortran, and has been used to predict the SPL for a certain configuration of buildings with different positions for the source, and different building densities. The model has demonstrated agreement with the expected behaviour from these geometrical configurations. Before applying the model into a detailed investigation of sound propagation through the urban fabric, it will be important to introduce the atmospheric attenuation, and an exchange coefficient related to the absorption coefficient of the building faces, to take account of the wall absorption. Then the diffusion computer model could form the basis of a simple prediction technique to account for the propagation of sound through the urban pattern.

7. REFERENCES

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