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THE PREDICTION OF NOISE PROPAGATION IN CITY STREETS

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1. INTRODUCTION

The way in which noise propagates down city streets is still not fully understood. Although various phenomena can be identified as having an effect on sound propagation in urban areas eg (geometric spreading, reflection and diffraction) the relative importance of these in any given situation is not clear. A comprehensive model capable of dealing with a variety of complex situations is needed in order to perform a systematic investigation of the sound propagation in city streets. The availability of simple prediction equations or charts for predicting the propagation characteristics of city streets could be of benefit to the urban designer.

Most previous work on street propagation has been based on the concept of specular reflections and for the case of ideal smooth streets{1-4}. Slightly more realistic geometries such as streets which have a regular pattern of protrusions or few wide gaps in their facades have also been studied[5-7]. Real streets which might have mixed or different patterns of protrusions and gaps cannot be dealt with by any of the models developed.

Prediction methods in many areas of acoustics have been developed based upon three approaches. These are measurements made on actual sites, measurements on acoustic scale models and theoretical models. Computer modelling was judged to be the most promising technique for the investigation to be undertaken in this work. In this paper the development of a computer model to study the noise propagation characteristic of urban areas will be described. The assumptions made in devising this model are validated against measurements made on scale models and finally, the results obtained from this work are used to devise simple charts for use by the urban designer.

2. A COMPUTER MODEL FOR THE PREDICTION OF NOISE PROPAGATION DOWN STREETS

The model is based on the use of image sources and/or receivers. It is assumed that a sound source in front of a smooth reflective plane surface produces an image source at the same distance behind that surface. By placing a sound source in an enclosure an array of image sources is obtained behind each plane and each successive image plane. The sound power level of each image source is adjusted according to its order and the absorption coefficients of the surfaces.

The sound intensity at a particular receiver position can be considered to result from the summation of the intensities of direct and indirect sound. Since the sound source is assumed to operate continuously and to emit broadband noise, it is assumed that there is no interference between direct and reflected waves as the effect of multiple reflections can be expected to "smooth out" interference dips. In the computer model developed in this work ground effect is approximated by adding 3 dB to the predicted levels. This is equivalent to the assumption of a perfectly reflecting ground surface.

Building facades have been reported as having an average reflection coefficient between 0.9 and 0.95 [7-9]. As a result of consideration of the above information the reflection coefficient of the simulated buildings in the computer model was taken to be 0.9.

The geometry of the street is defined in terms of Cartesian co-ordinates. The X-axis is assumed to pass through the source point, the Y-axis is assumed to pass through the receiver point and the Z-axis is perpendicular to both the X and Y axes and used to define height. Vertical reflecting surfaces alongside the street are defined by YZ planes.

After identifying the street layout and defining the position of both source and receiver the direct sound level at the receiver is calculated.

If there is no obstacle between the source (S) and receiver (R) the direct sound level at (R) is given by:

$$L_R = L_{ref} + 20\log(d_{SR}/d_{ref}) \quad \text{dBA} \qquad (1)$$

where L_{ref} is the sound pressure level from the source at reference distance (d_{ref}) and d_{SR} is the direct distance between source and receiver.

The program considers the reflected rays to undergo from one to eight reflections. It was decided to limit the number of reflections considered to the eighth order since it was found that the inclusion of higher orders produces only a minor contribution to the total level experienced at the receiver [10,11].

The sound pressure level at the receiver due to any reflected ray is given by:

$$L_R = L_{ref} + 20\log(d_{SR}/d_{ref}) + 10\log((1-\alpha)n \qquad (2)$$

Where n is the order of reflection, α is the absorption coefficient of the facades and d_{SR} is again the path length of the ray from Source to Receiver.

The first stage in calculating the contribution due to reflections is the construction of all the possible images of the receiver in the reflecting planes on both sides of the street. All the vertical surfaces on each side of the street are assumed to be in two planes. These planes are denoted by A and B on one side and planes C and D on the other side. This results in four first order images of the receiver (R). These images can be denoted by subscripts a, b, c and d which relate to the reflecting surfaces involved (see Figure 1).

The source is assumed to emit rays in the direction of the four images, and the program checks to find if any of these rays intersect with any part of its corresponding reflecting plane. If a ray does not encounter any obstacles on the way it is assumed to be reflected to the receiver position. However, if it encounters another plane in the 'Y' direction the ray is considered to undergo diffraction. Figure 1 illustrates the possibilities for first order reflections.

For rays undergoing two reflections the program calculates the co-ordinates of the second order images, these are the images of each of the first order images in the two planes on the opposite side of the street. This yields eight images denoted by subscripts ad, bd, ac, bc, cb, ca, db and da, where the first letter denotes the first reflecting plane and the second letter denotes the second reflecting plane. The ray is first traced between the source and the second order image, if the ray is found to be specularly reflected, the program then traces the ray from the reflection point to the first order image.

Extension of this approach to higher order reflections is straightforward. However, in the computer model it was found that no advantage was to be gained from employing higher than eighth order reflections [10,11].

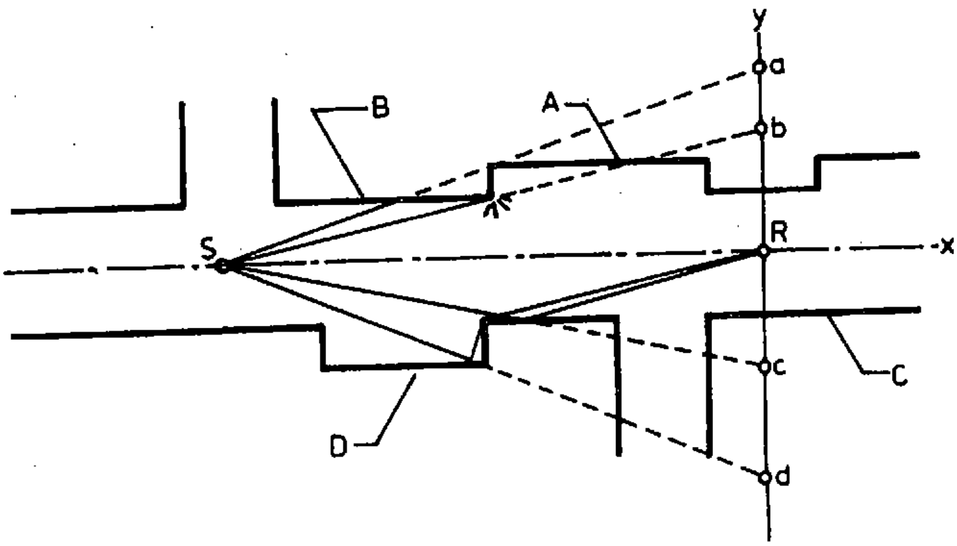

Figure 1. First order images showing possible sound paths

Consideration of the phenomenon of diffraction in this model is limited to situations where there is no direct path between source and receiver due to the presence of an obstacle or where a ray is specularly reflected in all planes apart from the last one.

3. THE SCALE MODEL

The objective of the scale model experiment was to validate and test the following assumptions made in developing the computer model:

(i) Interference between sound at the receiver arriving via different paths is not significant
(ii) The height of the flanking walls is not significant
(iii) Restricting the number of reflections to eighth order caused no problems
(iv)The simple model used to predict the effect of diffraction and scattering is adequate

A maximum propagation distance of 200m was used in the computer model which is a typical distance over which propagation effects are important in urban areas. For streets of this length to be modelled in the available anechoic chamber resulted in the choice of a scale factor of 1/32.

As traffic is the dominant noise source in urban areas, the range of frequencies taken into consideration was that of the traffic noise spectrum. From an examination of an 'A' weighted traffic noise spectrum given by Delany, Rennie and Collins [9], it can be seen that the range of effective frequencies is from 50 Hz to 2.5 kHz. It can also be seen that the 'A' weighted spectrum contains less energy at the low frequencies than at the higher ones and it can be assumed that the lower frequencies make a minor contribution to the total level of noise produced by sources such as traffic. The range of frequencies considered in this work was, therefore, 2 to 63 kHz corresponding to 63 to 2 kHz in the prototype situation.

A jet-source similar to that developed by Delany, Rennie and Collins [9] was chosen for this work as it was compact, omni-directional, produced sound with adequate signal to noise ratio and was free of pure tones.

In urban streets the ground is mainly pavement or asphalt and building facades are typically of brickwork, concrete and glass. The material chosen to simulate the building facades should have reflection characteristics at the relevant model frequencies, similar to those of the simulated facade materials at prototype frequencies. Chipboard was selected as a possible material as it is inexpensive, durable and easy to work. A secondary experiment was therefore carried out in order to measure the reflective properties of chipboard at the high frequencies to be employed in this work. The impulse technique was employed to measure the reflection characteristics of the chipboard.

The chipboard was tested at various angles of incidence. The average values of the pressure reflection coefficient and the standard deviation values.The pressure reflection coefficient was approximately 0.95 (which is equivalent to an intensity reflection coefficient of 0.9) over the frequency range of interest. The above results suggested that chipboard could be used to construct the scale model with no further treatment.

Excess attenuation due to absorption of sound in air is a common problem encountered in acoustic scale model work. In this work calculating the amount of air absorption and employing the calculated values to correct the measurements was deemed the most appropriate the technique for overcoming this problem.

Three main types of single streets have been considered in this work, they are smooth streets, streets with regular protrusions and streets having gaps in their side walls. These types will be called smooth, regular and gap streets respectively (see Figure 2). Different arrangements have been used for the protrusions of the regular streets. The basic pattern consisted of protrusion of 1m depth and 3m width with 10m spacing between them. An additional set of protrusions could be added to this basic model at different positions i.e. at the middle of the spacing, on top or next to the basic protrusions. The resultant arrangements are referred to as double protrusions, large protrusions and wide protrusions. The widths of the streets investigated were 10, 20 and 30 metres.

The anechoic chamber floor was covered by chipboard panels on which the models were arranged to form the required street pattern. The sound source was recessed in holes made at appropriate places in the model street. The height of the source above the floor level was 3.0 cm, corresponding to the average source height of road traffic in the prototype.

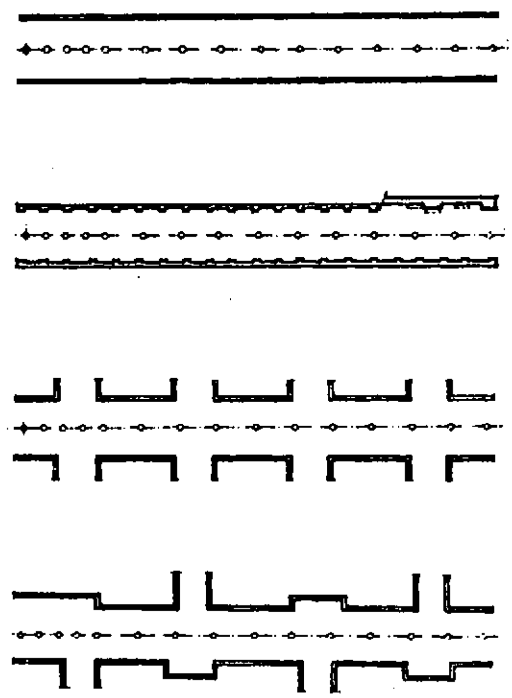

Figure 2. Street configurations: from top to bottom, smooth, regular, gap and mixed. (o = source position)

The measuring microphone was held by a suspension system which allowed the microphone to be moved in the three directions with the diaphragm directed downwards.The height of the microphone was taken to be the height of a ground floor window.

4. VALIDATION OF COMPUTER MODEL

The results obtained from both the computer model and the scale model used in the comparisons were both normalised with respect to the free field noise level at a distance of 7.5 metres. Results of the scale model measurements were obtained at 1/3 octave band frequencies in the range of 2-63 kHz which corresponds to 63 Hz to 2 kHz in the full scale. Comparisons were made at these sixteen centre frequencies.

An assumption made in developing the computer model was intially checked at the start of the scale model experiment. This relates to the ground effect and the importance of multiple reflections between the walls of streets in reducing interference effects. The ground effect has been assumed in the computer models to double the source power i.e. add 3 dB to the predicted sound pressure level. This assumption was verified in the scale model by measuring the distance attenuation curves with the source located above the ground (chipboard) with no walls in place. Approximating the ground effect by adding 3 dB appeared a reasonable assumption in spite of the dips observed at some frequencies at different distances. These dips became much less significant for the measured distance attenuation curves with flanking walls in place especially for the case of non smooth facades where the effect of protrusions was to scatter the sound rather than to specularly reflect it.

The influence of the height of the flanking buildings of streets on the resultant noise level was investigated in this work by means of scale model measurements. It should be noted that in the computer model developed in this work the effect of building height is not considered. Two types of streets (smooth and regular streets) with widths of 10, 20 and 30 metres were modelled for three different heights of flanking buildings corresponding to 2nd, 4th and 6th storey buildings. It was observed that there is no systematic difference between the results for low and high buildings.

From these results it can be concluded that the height of flanking buildings has no effect on noise levels within the range of geometries employed in this work as long as the height of both the receiver and the source is less than the height of the surrounding buildings.

Comparisons between measured and predicted distance attenuation curves have been made for a number of street types. The agreement between calculated and measured curves was generally good. Some systematic discrepancies were observed at the four highest frequencies employed corresponding to 31.5, 40, 50 and 63 kHz in the scale model. At these frequencies measured noise levels are always lower than predicted noise levels.

It was concluded that the observed systematic discrepancy between measurements and predictions at the highest frequencies are partially due to the directivity of the sound source and microphone and the surface roughness of the elements of the model.

The relation between predicted values and the measurements of distance attenuation can be evaluated for the whole range of frequencies emitted by a broad band noise source. The most common noise source in urban areas is road traffic and by summing the components of the A-weighted spectrum of a single vehicle, the attenuation characteristics of a street for noise from a road vehicle can be determined.

5. THE PREDICTIVE MODEL

On examination of the data obtained it could be seen that the distance attenuation curves obtained from the computer model are similar to those measured on the scale model for the low and mid-range frequencies. For the purposes of statistically relating the two sets of data and for ease of comparison of the propagation of different street types it is useful to fit a smooth curve to the data for each street type. From an examination of the data there appeared to be no significant advantage in fitting other than a linear regression curve of attenuation against logarithmic distance.

One of the mid-range third octave bands (500 Hz) was selected for a statistical study of the results as this is the frequency often used for preliminary design purposes. The predictions are in fact almost frequency independent because diffraction, which is the sole phenomenon considered in the computer model to depend upon frequency, has been found to have very little effect. Linear regression lines were fitted to both sets of data and the 95% confidence limits calculated. The analysis has been made for each type of street for the three widths of 10, 20 and 30 metres. The statistical analysis has been applied first to the predictions and then to the measurements. In order to allow the trend of both sets of data to be compared, the regression lines obtained from the predictions were superimposed on the graphs of the measurements.

The effect of varying the street widths on noise propagation was observed to be similar for both techniques. However, the scale model results were normally found to have a greater degree of scatter than the computer model predictions

The coefficients of the regression lines of smooth, regular and gap streets were used to demonstrate the effect of the width of these types of streets. The results for smooth streets show that wider streets yield a lower sound level than the narrower streets at the same distance from the source. This difference becomes smaller at greater source-receiver distances.

The interpretation of this feature is that the reflected rays have longer distances to travel from source to receiver via the side walls than is the case for the narrower streets, hence there is less noise at the receiver. The effect of width becomes less important for rays traveling long distances.

A different characteristic was observed for propagation down regular streets. Wider streets produce lower noise levels at receiver positions relatively close to the source but away from the source narrow streets are found to produce noise levels lower than in the wider streets. Although sound rays in this case would still undergo the same distance effect as in smooth streets, another mechanism is acting at large source-receiver distances. The angle between incident and reflected rays is largest for narrow streets and remote receivers, this makes these rays more likely to be obstructed by protrusions than rays in wide streets and with receivers close to the source.

Figure 3 shows a comparison of results for the scale model and computer model for regular streets with double protrusions. The figure shows the linear regression of scale model measurements with the computer regression line. The good agreement between measurement and predictions is apparent from the similarity between the regression lines of the measurements and the predictions. This good agreement was observed for all street arrangements that were investigated.

The comparison between the regression characteristics for gap streets shows that these lines merge together at large source-receiver distances. This feature demonstrates again the effect of street width on the reflected rays. Narrow smooth streets were found to produce higher noise levels as a result of stronger reflections but introducing gaps attenuates these reflections. This effect yields similar noise levels for streets of different widths at long source-receiver distances.

Table 1 shows a comparison of the regression coefficients obtained for each of the street types examined. The propagation characteristics of the streets are expressed in the form of the following equation.

$$L_{ATT} = A + B \log x/7.5$$

Where

L_{ATT} is the attenuation

and

x is the source-receiver distance.

The level, L, at a distance x metres from the source is given by:

$$L = L_{7.5} + L_{ATT}$$

where $L_{7.5}$ is the noise level measured at 7.5m from the source.

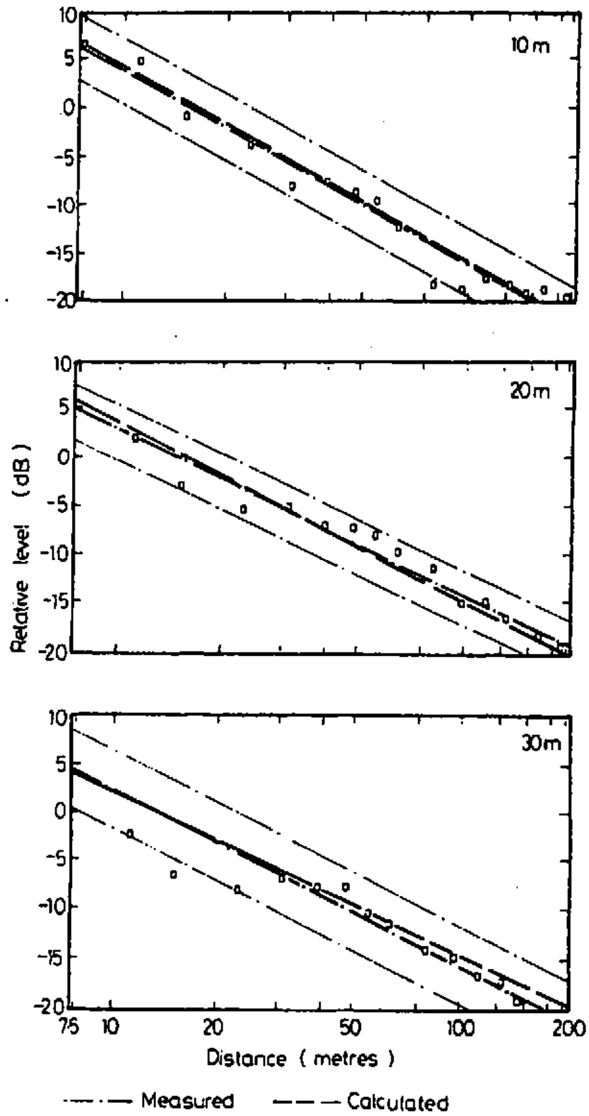

Figure 3. Linear regression of scale model measurements for regular streets with double protrusions showing both computer and scale model regression lines. - - - - = computer; - - - - = scale model.

Street Type	Street Width					
	10m		20m		30m	
	A	B	A	B	A	B
Smooth	7.47	-14.34	4.92	-13.36	3.69	-13.20
Regular	9.33	-21.30	6.16	-17.28	4.75	-15.85
Regular Large	7.05	-20.08	6.09	-18.88	4.78	-17.64
Regular Wide	8.97	-20.10	6.16	-17.28	4.01	-14.74
Regular Double	7.71	-21.52	6.07	-19.77	4.42	-17.49
Gap	6.51	-16.71	4.38	-15.49	3.09	-14.09
Average Street	**8.3**	**-20.8**	**6.1**	**-18.3**	**4.5**	**-16.4**

Table 1 Regression coefficients of single streets

From Table 1 it can be seen that for street types other than the smooth or gap streets the values of the coefficients A and B are similar for streets of the same width. The smooth street is obviously an unrealistic case and the properties of the gap street will depend upon the percentage of the flanking facades occupied by gaps.

The similarity of the coefficients for all the street types other than smooth and gap suggests that for streets lined by a continuous row of buildings, a common prediction equation can be used without significant loss of accuracy. This has been obtained by averaging the coefficients for the four such street types considered in this work. These coefficients are also shown in Table 1 and denoted "average street". It can be seen that the coefficients are functions of the street width. This suggests that there exists a possible relationship between the coefficients A and B and the street width which, if determined, could form the basis of a simple predictive technique. The computer simulation program was run again to determine the coefficients for a variety of street widths for streets having a random arrangement of protrusions and (for greater realism) a few gaps.

The results of this investigation are shown in Figure 4 where the coefficients are plotted against the inverse of street width. From the regression equation shown on Figure 4, the followingsimple equations for predicting the propagation coefficients can be derived:

A = 3 + 50/w and B = -(15 + 40/w) where w is the street width in metres.

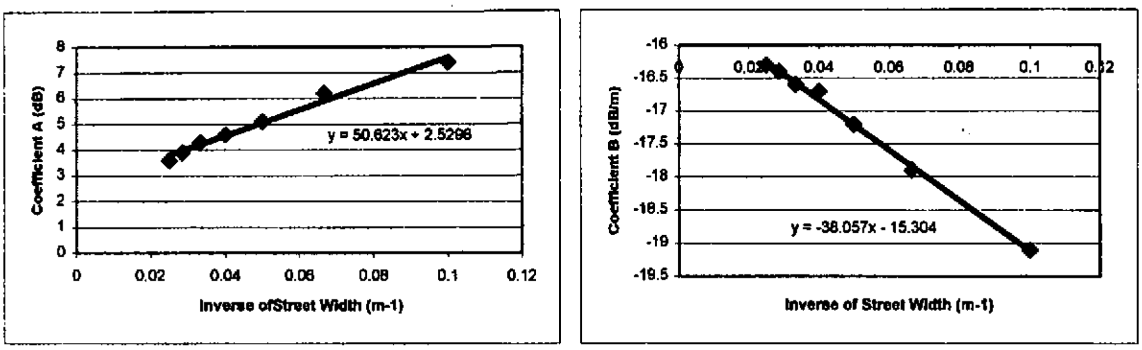

Figure 4. Coefficients of the street propagation predictive equation.

6. CONCLUSIONS

The assumptions made in constructing the computer model described in this paper have been validated against measurements made on an acoustic scale model. Although the regression lines for both the computer simulation and scale model results were similar, the scale model data points tended to be grouped around the regression line in a systematic manner. The regression characteristics were such as to provide the basis of a design method capable of predicting narrow band noise levels arising from the operation of a point source in a city street.

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