A COMPUTER MODEL FOR THE PREDICTION OF NOISE LEVELS IN FACTORIES

C.J. Jones and B.M. Shield

Institute of Environmental Engineering
South Bank Polytechnic
London.

Introduction

A computer model for the prediction of factory noise levels was developed during the 1970s [1]. The aim was to provide a factory manager or designer with a simple tool whereby the effects on overall noise levels around a shop floor of various noise control measures such as reorganising the plant layout or quietening or removing noisy machines could be evaluated.

The original model uses a simple ray tracing method for the calculation of sound levels. Various modifications have been made to the model and the original data reanalysed in an attempt to improve its accuracy. New data have also been collected in factory spaces and used in further validation of the model.

Description of the model

Data The model calculates sound levels around a shop floor at any number of receiver points whose positions are specified by the user. Room dimensions, absorption coefficients of all the room surfaces, and positions and sound levels of individual machines are input as data.

For each machine a set of sound pressure levels is input. These are measured according to the 1972 British Standard BS 4813 "Method of measuring noise from machine tools" [2], in which sound pressure levels are measured at several points around a machine, at a distance of one metre from the machine surface and a height of 1.5 metres. These sound pressure levels are converted to intensity (in Watts/m^2) and averaged by the program to give, for each machine, the average intensity at a distance of one metre.

During the development of the model several methods of determining sound levels from machines were investigated, both for ease of use on a shop floor and to see which method produced the most accurate predictions from the program. The BS 4813 method proved most suitable on both counts. The program has recently been modified so that manufacturers' information on sound power output of machines can be input as data if required.

Absorption coefficients for the original model were obtained from standard tables such as those of Evans and Bazley [3]. In the recent work carried out on the model results using these figures have been compared with results predicted using an average absorption coefficient obtained by measuring reverberation times.

Calculation of sound levels In the original model the sound level at each receiver point was obtained by adding the direct and reflected sound from each machine, the reflected sound being obtained by considering one reflection off each room surface, as shown in figure 1.

If I is the average intensity in Watts/m^2 of sound at a distance of one metre from a machine then the intensity of direct sound at a distance of r metres is equal to I/r^2 W/m^2. Considering the sound reflected off a particular room surface, if the distance travelled by the reflected wave is d metres, and the absorption coefficient of the surface is α, then the intensity of the relected sound is $I(1 - \alpha)/d^2$ W/m^2.

However, as described below, when validating the program it was found necessary to vary the index of r and d between 1.5 and 2.0. Thus

intensity of direct sound = I/r^p W/m^2 where $1.5 \le p \le 2.0$

and

intensity of total sound at a receiver point, in W/m^2, is given by

$$\sum_{m=1}^{M} I_m\{1/r_m^p + (1-\alpha_1)/d_1^p + (1-\alpha_2)/d_2^p + \ldots + (1-\alpha_w)/d_w^p + (1-\alpha_c)/d_c^p + (1-\alpha_f)/d_f^p \qquad (1)$$

where M is number of machines; I_m is intensity of sound of machine m at a distance of one metre; r_m is distance from receiver point to machine m; W is number of walls; α_i is absorption coefficient of wall i; d_i is distance travelled by reflection off wall i; α_c, α_f are absorption coefficients of ceiling and floor; d_c, d_f are distances travelled by reflections off ceiling and floor; and $1.5 \le p \le 2.0$.

During development of the model the calculation procedure was refined in various ways, for example by considering multiple reflections off each room surface, but there was no significant improvement in accuracy. The final version therefore used the simple procedure for calculation of sound levels described above.

A version of the program has recently been developed and tested in which the reverberant sound level is calculated using the standard formula 4W/R where W is sound power and R is the room constant. Results from this version are discussed below.

Output The output consists of a list giving direct and reflected sound at each receiver point and a plan of the shop floor showing positions of machines and noise levels at all receiver points. Suitable graphics are to be developed to enhance the presentation of the output.

Validation of model

The original model was tested using data collected in several workshops and factories whose floor areas ranged in size from 100 m^2 to 3000 m^2. The numbers of machines measured at each site ranged from 1 to 125.

In order to test the accuracy of the model sound levels of individual machines were measured on the shop floor using the BS 4813 method, and overall noise levels were then measured at receiver points all around the floor with all machines running simultaneously. The individual measurements were input as data to the program, together with the relevant room characteristics, and predicted noise levels were compared with the levels measured at the receiver points.

Noise levels were measured and predicted in dB or dB(A), as appropriate, and also, where possible, in various octave bands.

It was found that in order to obtain consistently good agreement between measured and predicted noise levels it was necessary to vary the index p in formula (1) between 1.5 and 2.0. In most cases accurate predictions were obtained with p equal to 1.7, although in some cases values of p of 1.5 or 1.6 gave the best results.

In order to illustrate the performance of the model, and the necessity of varying the index p in formula (1), two case studies are described.

Case study 1 This was a small workshop in a factory manufacturing fishing tackle. The workshop measured 9m x 12m and contained six machines.

Measurements of overall noise levels were made in dB(A) at 25 receiver points and ranged from 84 to 90 dB(A). Sound levels of individual machines, measured by the BS 4813 method, ranged from 69 to 96 dB(A).

The most accurate results were obtained with p equal to 1.5. The mean error in this case was -0.04 dB(A) and standard deviation of errors 0.53 dB(A). The predicted level was within 1 dB(A) of the measured level at all 25 receiver points.

A scatter diagram of predicted plotted against measured levels is shown in figure 2.

Case study 2 This was a large cold heading shop occupying approximately 3000 m^2. It contained 125 machines of 25 different types.

The overall noise level was measured in linear dB at 71 points and ranged from 89 to 101 dB. Individual machine noise varied from 84 to 94 dB.

In this case the best results were obtained with index p equal to 1.7, giving a mean error of -.05 dB and standard deviation of errors of 1.23. The difference between predicted and measured levels was less than 2 dB at 67 of the 71 receiver points.

Predicted are plotted against measured levels in figure 3.

Accuracy at different frequencies Where noise levels were measured and predicted in different octave bands, accuracy was good in the middle frequency range, but below 500 Hz and above 8000 Hz results were less satisfactory.

Investigation of errors

In all cases the errors between predicted and measured levels were examined to see whether they were related to any of the folowing factors: floor area, ceiling height, room volume, number and density of machines. No correlation was found between the errors and any of these characteristics of the sites.

Modifications to the program

Attempts have recently been made to improve the accuracy of the program by considering alternative methods of calculating sound levels. The original data has been run in the modified versions of the program, and results compared with the previous predictions. Data has also been collected in an empty factory space, and used to compare the accuracy of the original model with that of the new versions.

Alternative method of calculating reverberant sound

It was decided to modify the original program so that the intensity of reflected sound was calculated using

$$\text{Intensity of reflected sound} = \sum_{m=1}^{M} 4W_m/R \quad W/m^2 \qquad (2)$$

where M is the number of machines; R is the room constant (m^2); W_m is the sound power (watts) of each machine.

The original data was adapted as follows so that it could be used to test this version of the program. The sound power level, H, of each machine was calculated using

$$H = L + 10 \log 2\pi r^2 \quad dB \qquad (3)$$

where L is the average sound pressure level (dB) at a distance r (in this case one metre) from the machine.

The average absorption coefficient of each workshop was calculated from the original coefficients of each surface and used to determine the room constant.

The intensity of direct sound was calculated as I/r^2.

Table 1 shows the mean errors and the standard deviations of errors for results from two sets of original data when run in both the original program with index p in formula (1) equal to 1.7; and the modified version of the program.

It can be seen that in both cases the most accurate results were obtained using the original program.

In order to make a further comparison between the original and modified programs new data was collected in an empty factory space, see figure 4.

Noise was generated in this space using a speaker and the resulting noise levels were measured at 79 receiver points around the room. Four sets of measurements were made with the speaker in four different positions as shown in figure 4. At each location the average sound pressure level of the speaker was determined using the BS 4813 method.

The new data was run in the original and modified programs, and the predicted levels compared with the measured levels at the receiver points. In the original program the index p was varied between 1.5 and 1.7. Table 2 shows the mean error and the standard deviation of errors at each speaker position for results from the original program, with p equal to 1.5, 1.6, and 1.7; and from the modified version of the program.

Again it can be seen that the best results were obtained using the original program. However the index p had to be varied according to speaker location in order to obtain consistently good agreement between measured and predicted levels.

For each speaker position the distribution of errors between measured values and those predicted by the original program with the appropriate value of p, was examined. It was found that error is a function of distance from the noise source, predicted levels being too high near the source, and too low at points furthest away from the source.

Use of reverberation time

It was thought that, as well as being related to distance from source, errors between predicted and measured values could be due to some extent to the incorrect estimation of absorption coefficients. It was therefore decided to measure the reverberation time of the empty factory space and use this to determine the average absorption coefficient of the room.

The original program was modified so that reflected sound could be calculated using an average absorption coefficient, rather than individual coefficients for each surface.

Using this method the error between predicted and measured levels was substantially increased.

The average absorption coefficient was also calculated using the estimated coefficient for each surface, and the reverberation time predicted using both the Sabine and Eyring formulae. In both cases there was a great discrepancy between calculated and measured RT values. This problem has previously been encountered [4] and supports other work [5] which shows that sound fields in factories are non-diffuse, and that in such enclosures the Sabine and Eyring theories are not valid.

Use of sound power

The program has also been modified so that the sound power of machines can be input directly. In formula (1) for the total intensity of sound at a receiver point, I_m (that is the intensity of sound of machine m at a distance of one metre) is replaced by $W_m/2\pi$, where W_m is the sound power of machine m. Further work will be done on determining the most appropriate method of measuring sound power for input to this version of the program.

Conclusion

It has been shown that a comparatively simple model of factory noise is capable of predicting noise levels to a high degree of accuracy, and performs at least as well as models based on traditional acoustic theory.

Further work is needed to discover what factors influence the choice of index p in the expression for sound intensity in the model.

The distribution of errors between predicted and measured sound levels will also be investigated in the hope of developing formulae for inclusion in the model which accurately describe the decay of sound with distance from a source.

Data will be collected in factory spaces of varying sizes in order to more fully test the model.

References

1. B.M.Shield. A computer model for the prediction of factory noise. Applied Acoustics 13, 471-486, 1980.

2. British Standards Institution. BS 4813, Method of measuring noise from machine tools. 1972.

3. E.J.Evans and E.N.Bazley. Sound absorbing materials. National Physical Laboratory, 1960.

4. W.Gabler. Schallschluckung, abschirmen und eingrenzen von storschall in industrienhallen. Schalltechnik 21,11-18,1961.

5. M.R.Hodgson. Surface absorption and scattering in enclosures. Proceedings of Acoustics '82, Guildford, A.3.4.1-A.3.4.4, 1982.

A COMPUTER MODEL FOR THE PREDICTION OF NOISE LEVELS IN FACTORIES

Table 1. Error analysis of two sets of original data. In both case studies the best results were obtained using p =1.7 in the original program.

Error = predicted noise level - measured noise level.

Data Set / Error Analysis	Original Program Index p =1.7	Modified Program
Data Set 1 Mean Error (dB) Std Dev of Errors (dB)	 -0.10 1.02	 3.05 1.06
Data Set 2 Mean Error (dB) Std Dev of Errors (dB)	 -0.70 1.47	 3.93 1.60

Table 2. Error analysis of data obtained in empty factory.

Error = predicted noise level - measured noise level.

Speaker Position / Error Analysis	Original Program Index p= 1.5	1.6	1.7	Modified Program
Position 1 Mean Error (dB) Std Dev of Errors (dB)	 1.03 1.14	 -0.34 1.29	 -1.71 1.49	 -1.07 1.98
Position 2 Mean Error (dB) Std Dev of Errors (dB)	 0.69 2.24	 -0.48 2.38	 -1.64 2.55	 -3.29 1.90
Position 3 Mean Error (dB) Std Dev of Errors (dB)	 2.41 1.28	 1.20 1.42	 -0.01 1.60	 -1.26 0.85
Position 4 Mean Error (dB) Std Dev of Errors (dB)	 -0.64 1.24	 -2.03 1.49	 -3.41 1.75	 -2.78 1.53

A COMPUTER MODEL FOR THE PREDICTION OF NOISE LEVELS IN FACTORIES

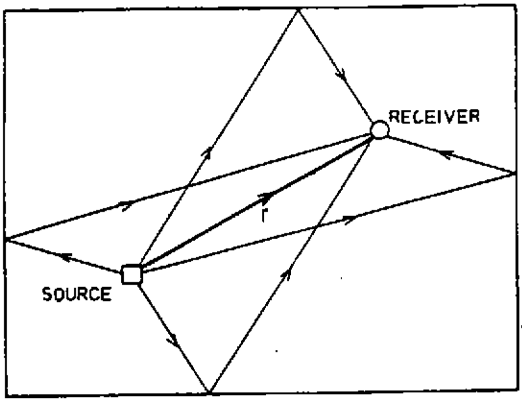

Figure 1. Paths of direct and reflected sound from source to receiver.

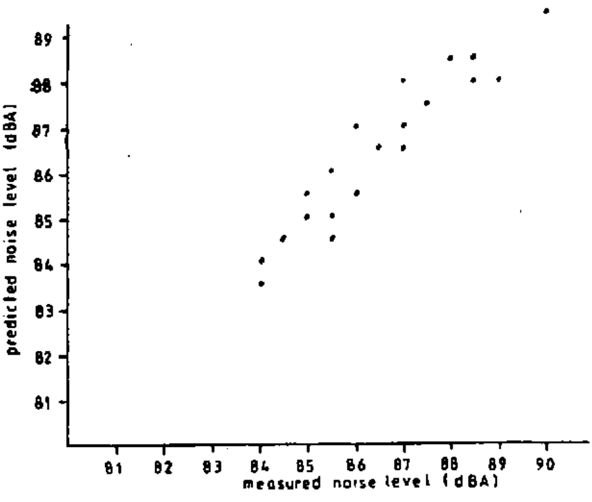

Figure 2. Case study 1 : predicted plotted against measured noise levels (p = 1.5)

A COMPUTER MODEL FOR THE PREDICTION OF NOISE LEVELS IN FACTORIES

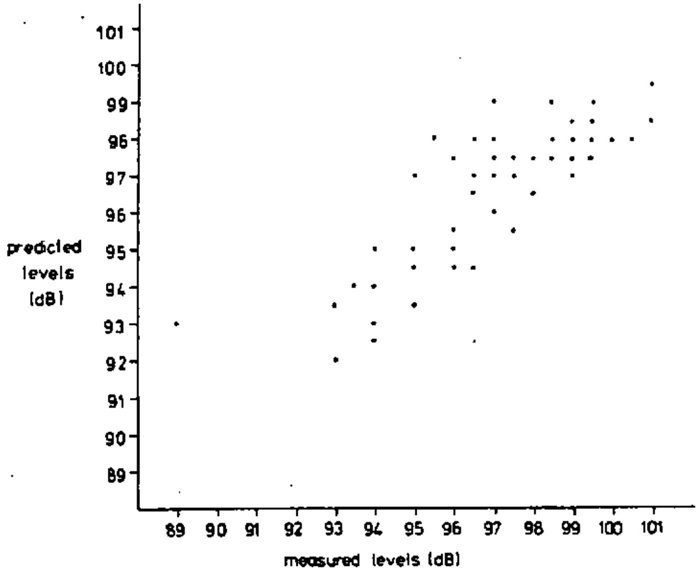

Figure 3. Case study 2 : predicted plotted against measured noise levels. (p = 1.7)

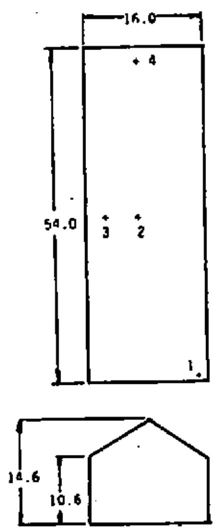

Figure 4. Plan and section of empty factory space showing its dimensions (in metres) and the speaker positions, + speaker position.