RAY-TRACING MODELLING OF NOISE IN A FOOD-PACKING HALL

Murray Hodgson

Occupational Hygiene Programme and Department of Mechanical Engineering
University of British Columbia, 2206 East Mall, Vancouver, BC Canada V6T 1Z3

David N. Lewis

Environmental Engineering Section, Unilever Research, Port Sunlight Laboratory
Quarry Road East, Bebington, Wirral, Merseyside, UK L63 3JW

ABSTRACT

By modelling workroom sound fields, the influence of building geometry, surface absorption, machine layout, sound power and directivity on noise at operator positions can be evaluated. This can be invaluable at the design stage of new projects or when assessing the most cost-effective approach to control noise in an existing installation. The approach adopted here is to predict the octave-band sound-propagation curves for a single noise source in the particular workroom using ray tracing. Curves are predicted for propagation in different directions within the building and for different acoustical treatments. They are approximated by one or two straight-line segments whose slope(s) are determined. A separate program is then used to compute the combined effect of all machine-noise sources in the workroom at positions on a 1-m grid, using the slope(s) and the applicable environmental correction factor. These techniques have been successfully applied to a number of major projects. Here, a case study is presented which illustrates a design-stage application to a new packing hall, which was modelled to evaluate the effects of increasing the ceiling absorption over all or part of the ceiling. The workroom is described and the predictions done are detailed. Also discussed are lessons learned with respect to workroom modelling.

SOMMAIRE

En modelisant le champ sonore d'un local de travail, il est possible d'évaluer l'importance de facteurs tels la géométrie du bâtiment, l'absorption de surface, la disposition des machines et la puissance et directivité du son sur les niveaux de bruit aux positions des opérateurs de machines. Ce procédé peut être inestimable au stage de la conception de nouveaux projets, ou pour évaluer l'approche la plus économique pour contrôler le bruit dans un bâtiment déja construit. L'approche adoptée ici est une prédiction des courbes de propagation du son (bande d'octaves) pour une source de bruit unique dans un environnement de travail particulier, en utilisant le traçage de rayons. Les courbes sont évaluées pour la propagation dans des directions différentes à l'intérieur du bâtiment, et pour des traitements acoustiques différents. Elles sont déterminées approximativement par un ou deux segments droits dont là ou les pentes sont évaluées. Un logiciel séparé est utilisé pour calculer l'effet combiné de toutes les sources de bruit-machine dans le bâtiment à des points de grille séparés de 1 metre, en utilisant les pentes et un facteur de correction environnemental. Ces techniques ont été appliquées avec succès sur un certain nombre de projets importants. Un cas pratique, qui illustre une application au niveau de la conception d'un atelier d'emballage, a été modelisé pour évaluer l'effet d'une augmentation de l'absorption du plafond sur une partie ou sur la surface totale. Le local est décrit, et les prédictions sont présentées en détail. Nous discutons aussi les leçons apprises en rapport au modelisation d'un local.

1. INTRODUCTION

Concern for worker health and safety - not to mention occupational noise regulations - require the noise exposure of employed persons to be assessed, and for measures to limit noise exposure to acceptable levels to be defined. In the case of regulations, there is usually a requirement to reduce noise exposure to the lowest reasonably practicable level by engineering and/or administrative means. Regulations usually only discuss noise levels; however, it is well known that excessive reverberation is another important factor that must also be considered.

By predicting workroom sound fields the influence of building geometry, surface absorption, and machine layout, sound power and directivity on reverberation times and noise levels at worker positions can be evaluated. This is invaluable when assessing the most cost-effective approach to controlling noise in existing installations or at the design stage of new projects.

The approach adopted in the case histories reported here was to predict the reverberation time (T_{60} in seconds) and/or the sound-propagation curves (the variation with distance, r, of the sound propagation, $SP(r)$, defined as the sound-pressure level, $L_p(r)$, minus the sound-power level, L_W, in dB) in octave bands for a single omnidirectional sound source in the workroom using ray-tracing techniques. Curves were predicted for propagation in different directions within the building and for different acoustical treatments. The curves were approximated by one or two straight-line segments. These segments are described by their slopes and absolute levels. The slopes were determined by regression, the absolute levels from applicable environmental correction factors. A separate program was then used to compute the combined effect of all noise sources in the building using the slopes and absolute levels of the sound-propoagation curves. This approach was considered more cost-effective than using ray tracing to calculate the total sound-pressure levels from the contributions of all of the sources; when many sources have to be considered run times can be prohibitive.

These techniques have been successfully applied to a number of major projects. A case study is presented here which illustrates their application at the design stage for a new food-packing hall which was modelled in order to evaluate the effects of increasing the acoustical absorption of all or part of the ceiling.

The aim of this paper is to illustrate the application of ray-tracing modelling techniques at a practical level. The case presented was a real-life study - contrained financially, technically and in time - done as part of the acoustical design of a facility. Time and cost constraints inevitably limit the effort that can be devoted to modelling. However, experience has shown that it can be a valuable tool to aid decision making in major projects. A further aim is to discuss what has been learned from the modelling exercise.

2. PREDICTION PROCEDURES

2.1 Sound-Propagation and Reverberation-Time Prediction by Ray Tracing.

Predictions of reverberation time and sound-propagation were made using ray-tracing techniques. The Ondet and Barbry model [1] for predicting sound-pressure levels in industrial workrooms with omnidirectional sound sources - extended to predict reverberation time - was used. More detailed descriptions of the model and its application are published elsewhere [1, 2].

Prediction involves modelling the workroom from a knowledge of the values of the following parameters at each prediction frequency: room geometry; surface absorption coefficients; fitting spatial distribution, densities and absorption coefficients; source sound-power level; source and receiver locations; air absorption exponent. Fitting density is quantified by frequency-invariant fitting scattering cross-section volume densities (in m^{-1}), typically assigned on the basis of experience as follows: nominally empty region, 0.03 [3]; low fitting density, 0.05-0.07; moderate fitting density, 0.08-0.17; substantial fitting density, 0.18-0.27; high fitting density, >0.27. The fitting absorption coefficient was 0.05 in all cases. Both fitting density and fitting absorption coefficient were assumed to be frequency invariant since this can give good results [2] and since the frequency variations are not known. The air-absorption-exponent values used in all predictions were those corresponding to a temperature of 20 °C and a relative humidity of 50 %.

The average slopes of the sound-propagation curves were determined from the slopes of least-square best-fit logarithmic regression lines through the predicted data, after approximating the curves by one or two straight-line segments - which ever gave the best results. Usually a single slope is accurate in smaller workrooms; a double slope may be more accurate in larger workrooms.

In all cases, once the room model was finalized, studies were done of the values of the ray-tracing parameters (the number of rays emitted by the source and the number of trajectories for which rays are traced) required to ensure accurate prediction in that case.

2.2 Sound-Pressure Level Prediction Using the Lewis Model

The combined effect of multiple noise sources within a workroom was modelled using a program ('the Lewis model') which computes the total A-weighted sound-pressure level at points on an imaginary 1-m grid over the workroom floor. Calculations can either be made in octave bands and the total A-weighted level computed. Alternatively, A-weighted levels can be derived from mid-frequency data; typically, industrial sound sources, such as packaging machines, have their highest sound powers in the 500-2000 Hz range. The program takes as input the horizontal coordinates of the machinery noise sources, their sound-power levels and information regarding their directivities (in two dimensions, defined as adjustments to the source sound-power level in six angular segments around the source). Constant-level background sources of noise (eg ventilation systems) are accounted for by logarithmically adding a constant background-noise level to the levels computed at all positions within the building.

The sound-propagation curves are assumed to comprise either one or two straight-line (on a logarithmic distance scale) segments. Each segment is described by its slope in dB/dd (dd means distance doubling) and its absolute level. The sound-propagation characteristics of the workroom can be input based on either a single-slope or a double-slope (eg 3 dB/dd up to 10 m and 4.2 dB/dd thereafter) curve shape. In addition, different propagation characteristics can be defined for different zones of the room. The values used for the slope(s) can be derived either from measured data, from empirical equations (for example, the Friberg [4] or Hodgson [5] models) or from predictions by more comprehensive approaches such as ray tracing. Absolute levels are estimated from applicable environmental correction factors [6].

The output from the program is a matrix of numbers representing the total A-weighted sound-pressure levels at positions 1 m apart over the floor of the building.

3. CASE HISTORY

3.1 Background

A new production / packaging facility was to be constructed inside an existing building. A design criterion of 85 dBA L_{Aeq} was set for maximum noise levels within it. Advice was requested on measures that could be taken to ensure that this target was met. The area of particular concern was secondary packaging, in which five production lines were to be installed. The proposed ceiling height in this area was 4 m. The floor dimensions were approximately 37 m by 35 m. Two bounding walls were of painted brick, the others of half-glazed plastic-faced steel-laminate partitions. The ceiling was intended to be of 'walk-on' construction, made of 50 mm plastic-faced steel-laminate panels. The floor was of concrete with a sealed epoxy finish. The fittings consisted of packaging and other machines and conveyors. A plan and elevation of the room showing the schematic machine layout are presented in Figure 1.

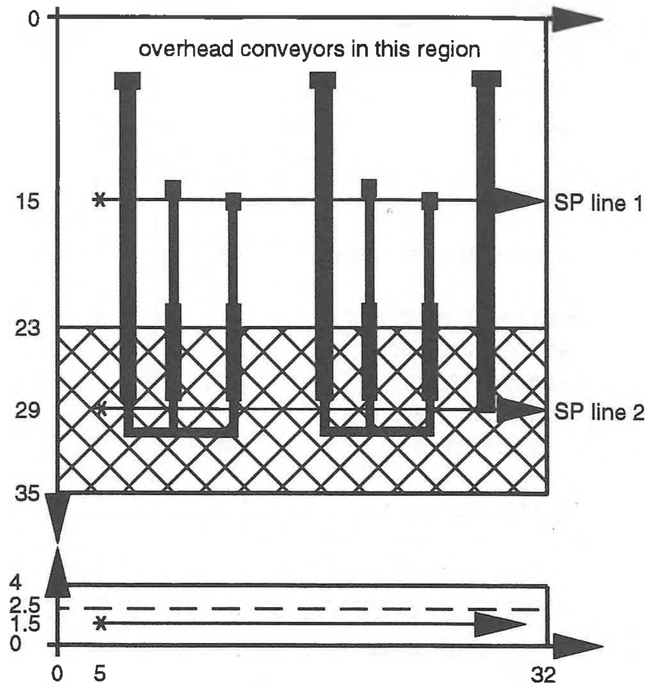

Figure 1. Plan and elevation of the food-packing hall as modelled, showing coordinated (in metres), sound propagation (SP) lines, extent of the partial ceiling treatment (cross-hatched) and the equipment layout (in black).

3.2 Ray-Tracing Prediction

Ray tracing was used to predict the mid-frequency reverberation times and octave-band sound-propagation curves, from which the average slopes were determined. Four cases were considered: a) without treatment (absorption coefficient, a= 0.07); b) moderately absorptive (a = 0.4) treatment of all of the ceiling; c) partial highly absorptive (a = 0.8) ceiling treatment - only one end of the ceiling was treated as shown in Figure 1; d) highly absorptive treatment of all of the ceiling.

The workroom was modelled from rough plan-and-section sketches showing the approximate machine layouts and heights, and from a knowledge of the internal untreated surface finishes. The room geometry was modelled - as shown in Figure 1 - and absorption coefficients for surfaces other than the ceiling were assigned as follows: floor, 0.02; vertical walls, 0.07. The room was divided into lower and

Table 1. Sound-propagation slopes and reverberation times (T_{60}) in the food-packing hall predicted by ray tracing

Case	Slope (dB/dd)	T_{60} (s)
A. Untreated	2.4	2.9
B. Moderate full treatment	3.8	1.6
C. High partial treatment:		1.9
- SP measured under untreated ceiling	2.7	
- SP measured under treated ceiling	4.6	
D. High full treatment	5.1	0.6

upper fitting zones delimited at a height of 2.0 m, the estimated average machine height. These zones were assigned fitting scattering cross-section volume densities as follows: lower zone, 0.15 m^{-1}; upper zone, 0.03 m^{-1}. The sound-propagation curve was predicted for a convenient source position and in a direction which crossed the production lines in a part of the room under the untreated portion of the ceiling in the partially treated ceiling case (SP line 1 in Figure 1). The number of rays emitted from the source was 25000; each was traced for 80 trajectories. The predicted slopes and reverberation times are shown in Table 1.

3.3 Sound-Pressure Level Prediction

At the initial phase of the project accurate sound-power levels for the machinery noise sources were not available.

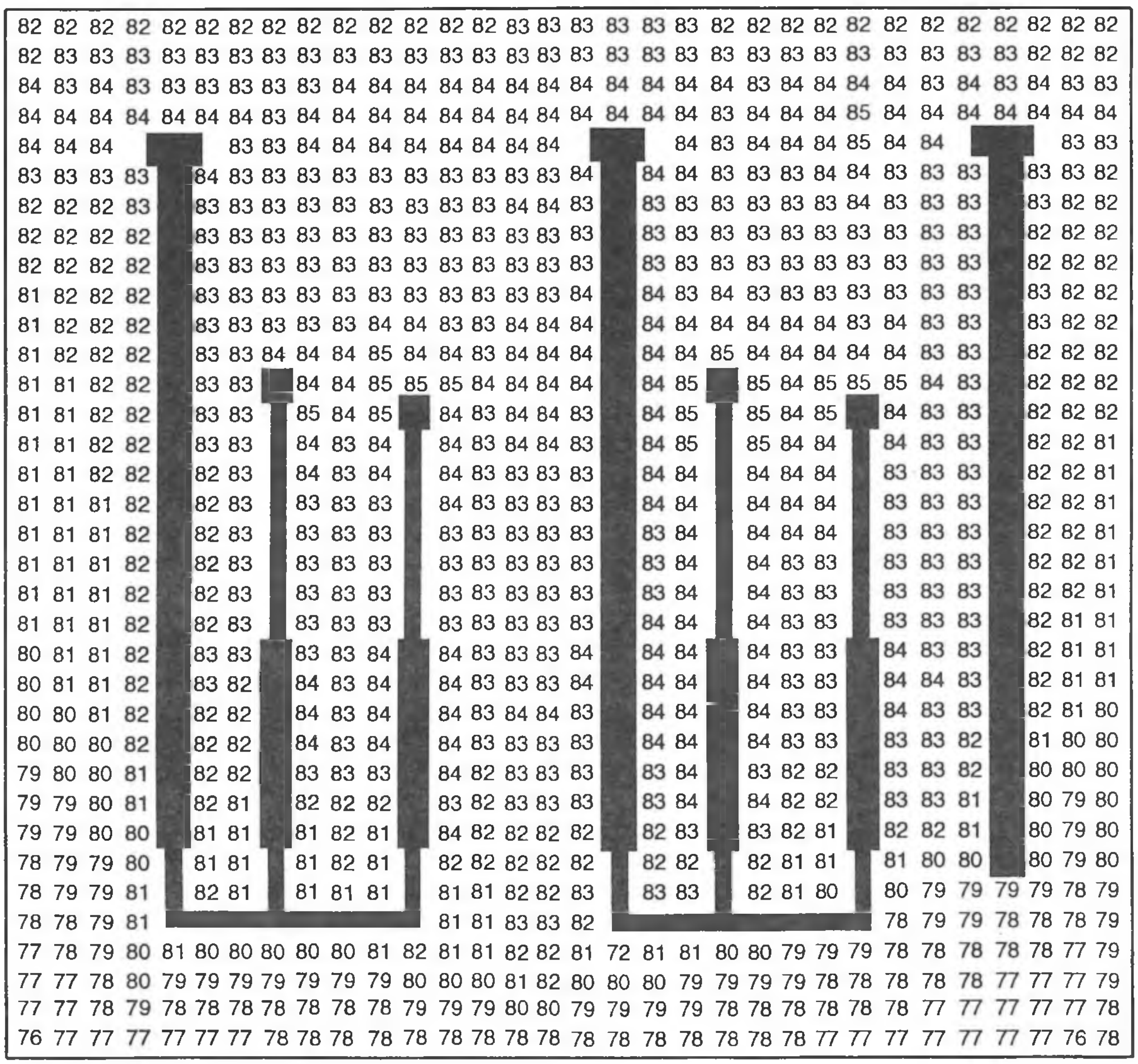

Figure 2. Predicted A-weighted sound-pressure levels in the food-packing hall with partial ceiling treatment.

Preliminary predictions were therefore based on estimates of sound-power level obtained from measurements on similar equipment or on those specified to the suppliers - as well as, of course, on the predicted sound propagation data. Each machine was represented as an array of point sources, with one point source per cubic metre of volume; in all, 41 sources were used to model the production lines illustrated in Figure 1. The expected A-weighted sound-pressure levels were computed for this array of noise sources for each of the ceiling-treatment cases described above. For example, in the untreated case levels varied from 83-85 dBA at operator positions near the production lines; in the partially treated case, levels varied from 80-83 dBA.

Due to the uncertainties in the input sound-power data it was decided that, in order to ensure that the design criteria would be met, some acoustical treatment of the building should be included. Following detailed discussions with factory engineers and architects, the noise-control option chosen was to replace the walk-on ceiling above the main packing machines (the cross-hatched area in Figure 1 - this was the noisiest area with the most operators) with an Ecophon Hygiene N acoustical ceiling with measured mid-frequency diffuse-field absorption coefficient near 1. The workroom was built with this treatment option implemented.

Although specifications had been given for the maximum permissible noise levels from the machines, tests during commissioning of the new workroom indicated that these had largely been ignored by the machine suppliers. Detailed noise studies were therefore conducted on the dominant sources, their power levels were determined, and a programme of control measures was implemented. In addition, the option of not enclosing four overhead conveyors which were to have run above the walk-on ceiling at one side of the room was considered.

At this time the opportunity was also taken to measure the sound-propagation curves and reverberation times in the new workroom. Using the slopes of the measured sound-propagation curves and the measured source sound-power levels the expected noise levels were recomputed in order to assess whether or not the design criterion would be met if the noise-control measures on the dominant machines were implemented, and if the conveyors were not enclosed. The results of the predictions are shown in Figure 2; for comparison, the noise levels measured under full production conditions are shown in Figure 3. The agreement was good - typically within 1 dB.

3.4 Final Remarks

The final treatment implemented was similar to prediction treatment case C. Thus it is instructive to compare predic-

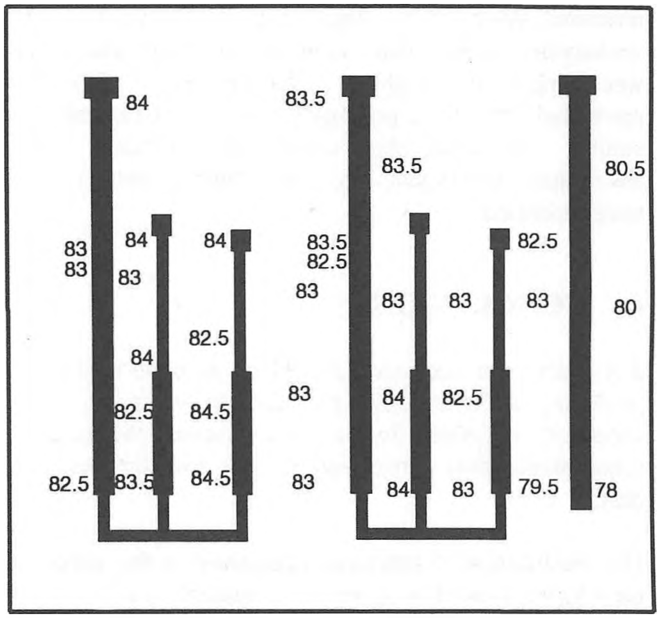

Figure 3. Measured A-weighted sound-pressure levels in the food-packing hall with partial ceiling treatment.

tions for this case with the results of measurement in the new workroom in order to evaluate the accuracy of the predictions done. The measured 125-8000 Hz octave-band reverberation times (in seconds) were as follows: 2.1 / 2.0 / 2.1 / 2.0 / 2.1 / 1.8 / 1.2. The predicted mid-frequency reverberation time was 1.9 s - only slightly lower than the measured values.

Figure 4 compares the predicted 1000-Hz sound-propagation curves for the partial-treatment case with those

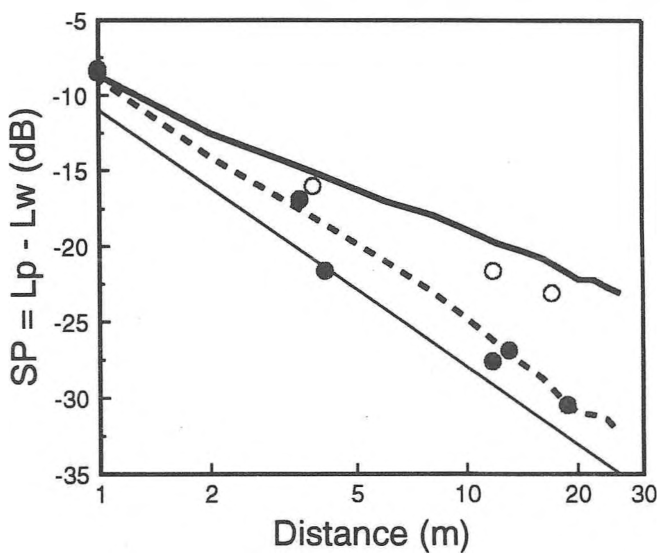

Figure 4. 1000-Hz sound propagation curves in the food-packing hall with partial ceiling treatment: under untreated ceiling - (O) measured, (▬▬) predicted; under treated ceiling - (●) measured, (▬ ▬ ▬) predicted. (———) free-field curve.

measured along the two lines shown in Figure 1. In the workroom as modelled, sound-propagation-curve slopes were apparently slightly underestimated. This was particularly true for a propagation line under the untreated ceiling, suggesting that either the untreated ceiling absorption coefficient or the fitting density was underestimated.

4. CONCLUSIONS

Ray tracing has been shown to be an accurate method for predicting workroom noise provided the workroom can be accurately modelled. In the cases presented the modelled sound-propagation curves agreed well with the measured data.

The combination of approaches presented in this paper has been found to work well and give valuable information to help decisions in major capital projects. In the applications to which this type of modelling has been applied the accuracy of the model has been found to be typically within 2 dBA provided the source data was valid.

REFERENCES

[1] A. M. Ondet, J. L. Barbry, "Modelling of sound propagation in fitted workshops using ray tracing", *J. Acoust. Soc. Am.* **85**(2) 787-796 (1989).

[2] M. R. Hodgson, "Case history: workroom noise prediction using ray tracing - validation and the effectiveness of noise-control measures", *Noise Control Engineering Journal* **33**(3) 97-104 (1989).

[3] M. R. Hodgson, "On the accuracy of models for predicting sound propagation in fitted rooms", *J. Acoust. Soc. Am.* **88**(2) 871-878 (1989).

[4] R. Friberg, "Noise reduction in industrial halls obtained by acoustical treatment of ceilings and walls", *Noise Cont. Vib. Red.*, 75-79 (March 1975).

[5] M. R. Hodgson, "Preliminary simplified model for predicting sound propagation in industrial workrooms", *Canadian Acoustics* 20(3) 37-38 (1992) and 20(4) 19 (1992).

[6] M. R. Hodgson, D. N. Lewis, "Environmental correction factors for typical industrial workrooms", *J. Acoust. Soc. Am.* **98**(3) 1510-1517 (1995).