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PRACTICAL APPLICATIONS OF RAY TRACING TO THE MODELLING OF FACTORY SOUND FIELDS

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1. INTRODUCTION

By predicting factory sound fields the influence of building geometry, surface absorption, and machine layout and sound power on reverberation times and noise levels at operator positions can be evaluated. The approach adopted in the case histories reported here was to predict the reverberation time and/or sound propagation curves (the variation with distance, r, of the sound propagation function, SPF(r), defined as the sound pressure level, Lp(r), minus the sound power level, Lw, in dB) in octave bands for a single omnidirectional sound source in the workroom using ray tracing. Curves were predicted for propagation in different directions within the building and for different acoustical treatments. A separate programme was then used to compute the combined effect of all noise sources in the building, using the average slopes and the absolute levels of these propagation curves. These techniques have been successfully applied to numerous major projects and the aim of the paper is to illustrate the application of modelling techniques at the practical level.

2. PREDICTION PROCEDURES

2.1 Sound Propagation and Rev. Time Prediction by Ray Tracing

Predictions of reverberation time and sound propagation function were done using ray-tracing techniques. The Ondet and Barbry model [1] for predicting sound pressure levels in industrial workrooms was used. It was extended to predict reverberation time. More detailed descriptions of the model and its application are published elsewhere [1,2,3]. Prediction involves modelling the workroom from a knowledge of the values of the following parameters at each prediction frequency; room geometry; surface absorption coefficient; fitting distribution, density and absorption coefficient; source power level; source and receiver locations; air absorption exponent. Fitting scattering cross-section volume densities (in m-1) were typically assigned as follows: 0.03 (nominally empty region [4]); 0.05-0.07 (low fitting density); 0.08-0.17 (moderate fitting density); 0.18-0.27 (substantial fitting density); >0.27 (high fitting density). The fitting absorption coefficient was 0.05 in all cases. The air absorption exponent values used in all predictions were those corresponding to a temperature of 20^{o}+C and a relative humidity of 50%. The average slopes and the absolute levels of the sound propagation curves were determined, respectively, from the slope and SPF value at a distance of 1m of the best-fit logarithmic regression line through the measured data. In all cases, once the room model was finalized, studies were done of the values of the ray-tracing parameters (number of rays emitted by the source, number of trajectories for which rays are traced) required to ensure accurate prediction in that case.

2.2 Sound Pressure Level Predictions using the Lewis Model

The combined effect of multiple noise sources within a work room was modelled using a programme (the Lewis model) which computes the total noise level at points on a 1m grid over the workroom floor. Calculations can either be made separately for each octave band and then the total level in dBA computed or a single calculation can be made based on dBA data. Typically, for sources which have their highest sound power in the 500 to 2kHz octave bands (which is generally the case for packaging equipment), calculations are restricted to dBA. The programme 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 in 6 angular segments around the source). Constant-level background sources of noise (eg ventilation systems) are accounted for by logarithmically adding a 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) sections. Each sections is described by its slope in dB/distance doubling (dd) and its absolute level (the value of the sound propagation function at 1 m). Thus, the sound propagation characteristics of the workroom can be input as either a single or double slope (eg 3 dB/dd up to 10m and 4.2 dB/dd thereafter) together with a correction to the computed sound pressure level at 1m. [5]. In addition, different propagation characteristics can be defined for different zones of the room. The values used for this parameter can be derived either from measured data, from empirical equations (for example, the Friberg model [6]) or from predictions by more comprehensive approaches such as ray tracing. The output from the programme is a matrix of numbers representing the total A-weighted sound pressure levels at positions 1m apart over the floor of the building.

3. CASE HISTORY 1

A new production/packaging facility was to be constructed inside an existing building. A design criterion of 85 dBA LAeq maximum was set for noise levels within the department. Unilever Research was requested to advise 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 4m. The floor dimensions were approximately 37m by 35m. Two 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 50mm plastic-faced steel-laminate panels. The floor was of concrete with a sealed epoxy finish. A plan of the room showing the schematic machine layout is presented in Fig. 1.

3.1 Ray-tracing Predictions

Ray tracing was used to predict the 1000-Hz reverberation time and octave-band sound propagation curve, from which the initial (2-10 m) slope and absolute level were determined. Four cases were considered: a) without treatment; b) moderately absorptive (a1000 Hz = 0.4) treatment of all of the ceiling; c) highly absorptive (a1000 Hz = 0.8)treatment of part of the ceiling (see Fig. 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 Fig. 1) and 1000-Hz absorption coefficients were assigned. The room was divided into lower and upper fitting zones delimited at a height of 2.5 m, the estimated average machine height. These zones were assigned fitting scattering cross-section volume densities. The sound propagation curve was predicted for a convenient source position and in a direction which crossed the production lines (see Fig. 1) in a part of the room under the untreated portion of the ceiling in the partially treated ceiling case. The number of rays emitted from the source was 25000; each was traced for 80 trajectories.

3.3 Sound Pressure Level Predictions

Preliminary predictions were based on estimates of sound power level obtained from measurements on similar equipment (as well as, of course, on the predicted sound propagation data) or those specified to the suppliers. Each machine was represented by an array of point sources, with one point source per cubic metre of volume; in all forty-one sources were used to model the production lines illustrated in Fig. 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. In the partially treated case, levels varied from 80 - 83dBA. Due to the uncertainty in the input sound power data it was decided that, in order to ensure that the design criterion would be met, some acoustic treatment of the building should be included. The noise-control option chosen and implemented was to replace the walk-on ceiling above the main packing machines (see Fig. 1) with an Ecophon Hygienic acoustical ceiling. This was potentially the noisiest area with the highest concentration of operators.

Although specifications had been given for the maximum permissible noise levels from the machines, tests during commissioning indicated that these had largely been ignored by the machine suppliers. Detailed noise studies were therefore conducted on the dominant sources 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 workroom and estimate the sound powers of the main noise sources.

Using these data the expected noise levels were recomputed in order to assess whether or not the design criterion would be met if the noise control measures were implemented on all dominant machines and if the conveyors were not enclosed. The results of the predictions are shown in Fig. 2; for comparison, the noise levels measured under full production conditions are shown in Fig. 3. As might be expected agreement was good, typically within 1 dBA.

4. CASE HISTORY 2

Noise levels within the canning department of a food factory were between 88 and 96 dBA. Unilever Research was requested to analyse the noise problem and advise on methods of noise control. The department contained six production lines, four of which typically operated at the same time. The machinery was mainly pneumatically operated, dosing product into empty cans prior to their being conveyed to banks of lidding machines. The dominant noise in the area, with a relatively flat spectrum between 500 Hz and 8 kHz, resulted from impact and pneumatic sources.

The packing hall was approximately 57m long by 34m wide, with a double-pitched, north-light roof extending between 5.6 and 9.6m height (see Fig. 4). The internal surfaces of the roof consisted of wood panelling, the walls were of painted brick and the floor was of epoxy-coated concrete. A sheet-metal screen, extending vertically from 2 to 4m, crossed the hall near one end. Machine heights were typically 1-2m; however there were numerous pipes, steel trusses and heating units within the roof space. Two target levels were defined, at 90 dBA and 85 dBA LAeq; the implications of achieving each of these targets were to be assessed.

4.2 Measurements and Results

Noise measurements were taken under three factory operating conditions in the untreated building as follows: i) Normal production (4 out of 6 lines operating); ii) During shut down at the end of a production shift, with line 3 operating alone; iii) Outside of production hours with no machines operating to: a) determine background noise levels from the ventilation systems; b) determine the noise emission of various sources operating alone; c) characterise the acoustical environment (according to the measured reverberation times and A-weighted sound propagation curves); d) identify the dominant sources of noise, the mechanisms of noise generation and possible approaches to noise control at source.

4.3 Initial sound pressure Level Predictions

From the measured data, predictions of workroom sound pressure level were done using the Lewis model. Initially each individual type of machine was modelled as an array of point sources with relative sound power levels and directivities adjusted until the measured near and far-field sound pressure levels were accurately predicted. Predictions were made for one line operating alone. Predictions were also made for four lines in operation and the combined effects of these, and of the ventilation systems, were computed. Comparison of the measured and predicted noise levels showed good agreement - typically within 1 dBA.

4.4 Noise Control Options

Two noise control approaches were considered: i) reduction of noise at the source (by modification, replacement or enclosure of the filling machines); ii) acoustical treatment of the ceiling (by treating existing surfaces or installing a suspended acoustic ceiling.) Using the measured slopes of the sound propagation curves for the untreated building, the effect of reducing the sound power of particular sources (by 5 to 10 dBA depending on the source) was predicted. The noise levels to be expected when two new production lines were installed to replace three old ones, were also estimated. In both cases noise levels in the vicinity of the production lines between 86 and 90 dBA were predicted. Before the effect of acoustic building treatment could be considered the relevant sound propagation curves had to be determined.

4.5 Ray-tracing Predictions

Ray tracing was used to predict the sound propagation curves and reverberation times in the factory for the 250-8000 Hz octave bands. The initial (ie 2 - 10 m) slopes of the sound propagation curves were then determined. Three cases were considered: i) without acoustical treatment; ii) with acoustical treatment of the non-glass parts of the existing pitched roof; iii) with a new suspended acoustical ceiling at 5.6m.

The following information was available when modelling the room: 250-8000 Hz octave-band reverberation times measured in the existing untreated building; photographs of the building and its contents; building plan and section drawings showing the machine layouts and approximate sizes; descriptions of the internal surface finishes; manufacturer's octave-band absorption coefficients for the absorptive ceiling treatments.
The following prediction procedure was followed:

1) the somewhat-simplified geometry of the building was modelled (see Fig. 4). A single source was located at a convenient characteristic position as shown. Surface absorption coefficients of the untreated and treated surfaces were assigned;

2) the volume was divided into six fitted zones. These comprised two horizontal zones delimited by the screen, since the equipment and, thus, the fitting densities on the two sides of the screen appeared to be significantly different. The volume was further divided into three vertical zones, delimited at 2 and 5.6 m. The lower layers contained all of the machines, the middle layers contained the upper parts of the higher machines, and the upper layers contained many pipes, trusses etc. Fitting densities and absorption coefficients were assigned;

3) Reverberation times were predicted for the untreated building. These were found to be about 10% higher than the

measured values at all frequencies. Thus, the fitting densities in the larger and smaller lower fitting zones were increased slightly. This resulted in excellent agreement between predicted and measured reverberation times. Thus these parameter values were used in all further predictions;

4) Reverberation times and sound propagation curves were predicted for the untreated and two treated cases. The initial slopes and absolute levels were calculated from the predicted curves. In all predictions 25000 rays were emitted from the source; each was traced for 75 trajectories.

4.6 Sound Pressure Level Predictions

Using the slopes of the sound propagation curves for the cases described above the expected sound pressure levels in the workroom were computed for various combinations of acoustic treatment and control at source. The results for a treated ceiling, and 5 to 10 dBA sound power reduction on the dominant sources is shown in Fig. 5. From this study it was concluded that a combination of noise control at source and acoustic treatment would be required to achieve the target noise levels. The engineering and cost implications of such noise control measures are currently being considered by the site.

5. REFERENCES

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MODELLING OF FACTORY SOUND FIELDS

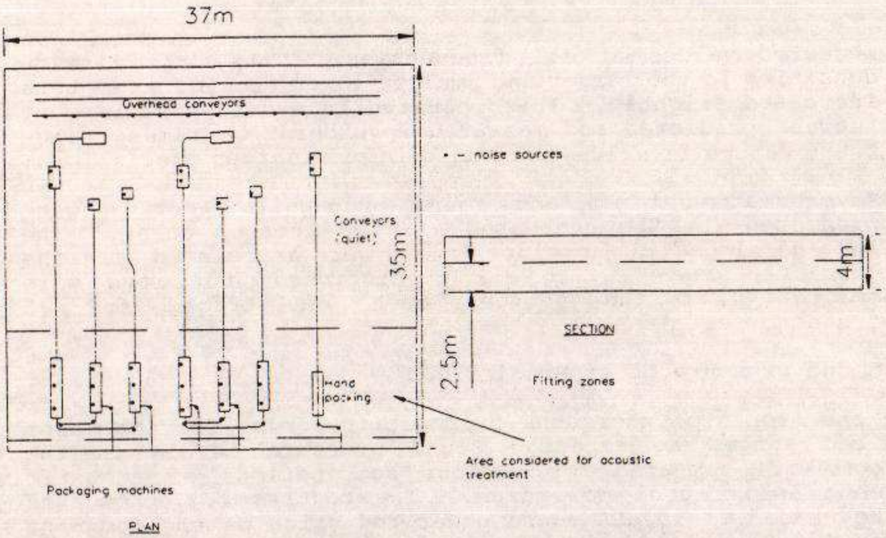
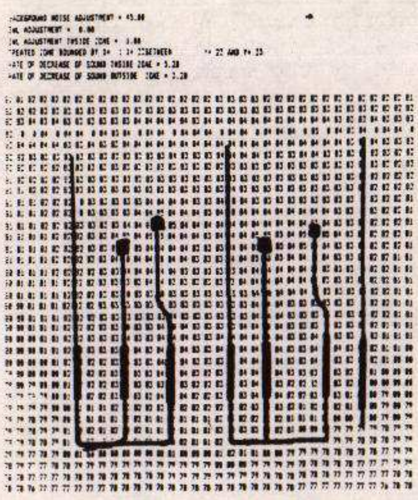
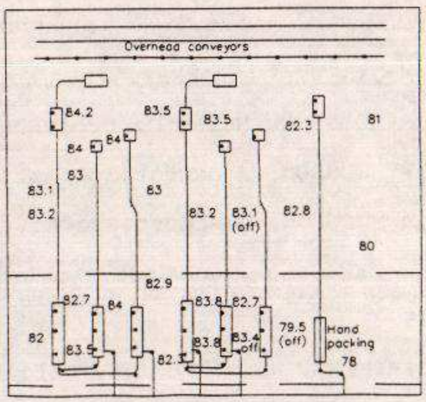


Figure 1



Noise levels dBA Leq - All Lines Operating
Overhead Conveyors On

Figure 2



Noise Levels dBA LAeq (1 minute) - Normal Production

Figure 3

MODELLING OF FACTORY SOUND FIELDS

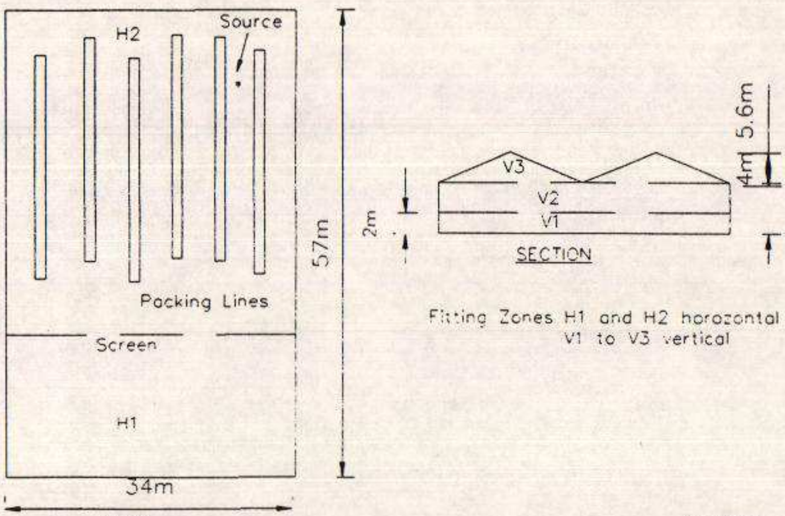


Figure 4

Noise Levels dBA - Lines 2,3,5 and 7 operating

Dominant sources reduced to 82 dBA. Ceiling acoustically treated

Background noise adjustment = 79.00

Initial rate of decrease of sound = 4.60

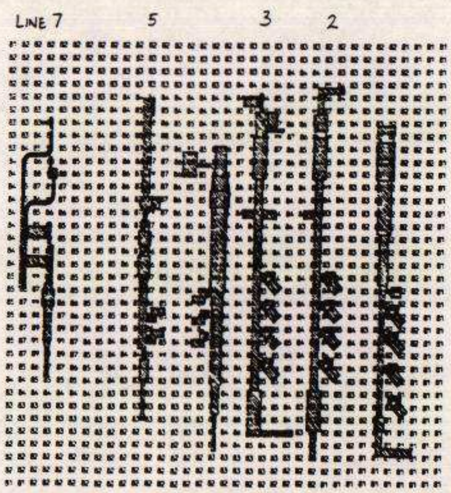


Figure 5