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EXPERIMENTAL VALIDATION OF A RAY-TRACING MODEL FOR FACTORY NOISE PREDICTION

by Murray HODGSON and Roland WOODCOCK
Département de génie mécanique
Université de Sherbrooke
Sherbrooke, Québec
CANADA, J1K 2R1

ABSTRACT

Factory-noise prediction models are invaluable in allowing worker noise-exposure levels in a factory to be evaluated prior to construction and, if necessary, for modifications to be made or noise-control measures to be evaluated. Ray-tracing techniques have proven to have the necessary accuracy and flexibility. In order to evaluate the accuracy of a ray-tracing model, comparisons were made between predicted and measured sound pressure levels for a machine shop with nine noise sources in operation. The shop was modelled using the known geometry, source and receiver positions, air absorption coefficients and the measured source sound power levels. Surface absorption coefficients were chosen on the basis of reverberation time measurements in similar factories when empty. The machine shop fitting density and absorption cofficients were chosen on the basis of previous research and by comparing the predicted and measured sound propagation curves for the shop, varying the fitting density to obtain a best-fit agreement. The ray-tracing model proved to give an excellent prediction accuracy.

SOMMAIRE

Les modèles de prédiction des niveaux sonores à l'intérieur des usines sont d'une très grande utilité pour évaluer l'exposition au bruit des travailleurs lors de la construction ou de la modification de ces usines ou encore lorsque les mesures de contrôle de bruit s'avèrent nécessaires. La méthode des rayons (ou "ray- tracing") apparaît aujourd'hui comme l'une des méthodes les plus flexibles tout en offrant une bonne précision. Pour évaluer la précision de cette méthode, des comparaisons ont été réalisées entre des niveaux prédits et des niveaux mesurés pour une salle d'usinage contenant neuf sources de bruit. La modélisation a été réalisée en utilisant les données bien connues de dimensions, positions de sources et de récepteurs, d'absorption d'air et des puissances sonores mesurées des sources. Les coefficients d'absorption des parois ont été évalués en utilisant les temps de réverbération mesurés dans des usines vides et de construction similaire. Les facteurs d'encombrement (densité et absorption) ont été choisis en se basant sur les résultats de recherches précédentes et en comparant des courbes théoriques et expérimentales de propagation du son à l'intérieur de la salle étudiée. Les résultats obtenus démontrent l'excellente précision que peut offrir la méthode des rayons.

1. INTRODUCTION

Accurate methods for modelling and predicting noise levels in factories are invaluable in the planning of factory buildings, equipment layouts and of potential noise-control measures. They permit worker noise-exposure levels to be estimated before the factory is built and its equipment purchased. If predictions show noise levels will excede admissible limits the factory building, and/or equipment and worker locations, can be modified. Further, the efficacy of potential noise- reduction measures - acoustic enclosures and screens, absorbent surface treatments etc - can be evaluated for their cost effectiveness.

Many theoretical and empirical models exist for predicting factory noise levels [1]. These are based on various approaches: diffuse-field theory; empirical formulae based on quantification of experimental trends; the method of images, whereby reflections from surfaces are replaced by image sources; ray tracing, whereby rays radiated by the sources are followed as they propagate in the room until they reach the receiver. The various models predict noise levels as a function of the relevant factory-acoustic parameters - room geometry, surface acoustic properties, room contents, source and receiver coordinates, source powers etc - to a greater or lesser extent. For example, diffuse-field theory does not account for the presence of room contents, which have been shown significantly to modify factory sound fields [2], nor of the exact room shape and the distribution of surface absorption. Existing empirical formulae approximate the sound propagation curve inaccurately and provide limited frequency information. Method of image models account for room shape, surface absorption distribution and room contents, but assume parallelepipedic shape and isotropically distributed contents. Only ray tracing models can account for arbitrary shape, as well as arbitrary absorption and contents distributions.

In previous research aimed at determining the relative accuracies of the various models, predictions have been compared with controlled experiments in idealized situations - specifically, in a scale model and in a warehouse with rectangular obstacles [3]. The conclusion of this study was that a ray-tracing model [4], specifically designed for predicting factory noise levels, is highly accurate.

Unfortunately, validation of ray tracing or other models in idealised situations does not guarantee the accuracy of predictions made for real factories. This is partly because real factories do not have, for example, rectangular fittings. Further, whereas the relevant values of certain parameters - for example, the geometry, source power, source and receiver locations - can be estimated a-priori with good accuracy, it is not yet known how accurately to determine that of other parameters, such as the surface absorption coefficients and the fitting density.

The objective of the study reported here was further to validate the ray-tracing model in the case of a real factory. This was done by comparing ray-tracing predictions with the results of controlled measurements made in a machine shop.

2. THE RAY-TRACING MODEL

The ray-tracing model used in this work was that developed by the INRS in France and modified by the author. Full details of this model are published elsewhere [4] - only a brief description is given here. Of particular interest to factories is its ability to model the effect of the enclosure contents - the fittings. The fittings are the various obstacles in the space which scatter and absorb propagating sound. The distribution of obstacles, which scatter omni-directionally, is assumed to follow a Poisson distribution. The factory volume is subdivided into a number of sub-volumes; each sub-volume is assigned a fitting scattering cross-section density and an absorption coefficient. As implemented the model simulates an enclosure defined by plane, specularly-reflecting surfaces whose absorptions are quantified by their absorption coefficients. Sources are assumed to be omni- directional points. Receivers are defined by a plane of cubic cells of a certain side length and located at a certain height. Diffraction effects (such as those relevant to sound propagation over partial-height partitions) are not modelled.

Briefly, the ray-tracing procedure occurs as follows: for each source a large number of rays, with random direction, are radiated. Each ray propagates from the source and is followed until it strikes the nearest surface or obstacle. The ray is then redirected according to the appropriate reflection law - specular reflection in the case of a surface, random reflection in the case of an obstacle - and followed until its next reflection, and so on for a sufficiently large number of trajectories. The power of the ray, initially related to the source power, decreases as the ray propagates, according to spherical divergence and surface, fitting and air absorption. For each trajectory a test is made to see if the ray traverses any of the receiver cells. If so the power of the ray is assigned to that of the cell(s) and the ray continues. The sound pressure level at each receiver position is calculated from the total power of the corresponding cell.

The ray-tracing model was programmed in FORTRAN, with its compiled version run on an IBM 4381-2 computer. Each sound level prediction (five octave bands) involved run times of up to two hours.

Figure 1 - Photograph of the machine shop showing the room geometry and fitting layout. The partial-height partition is visible at the far end; the doors were closed during all tests.

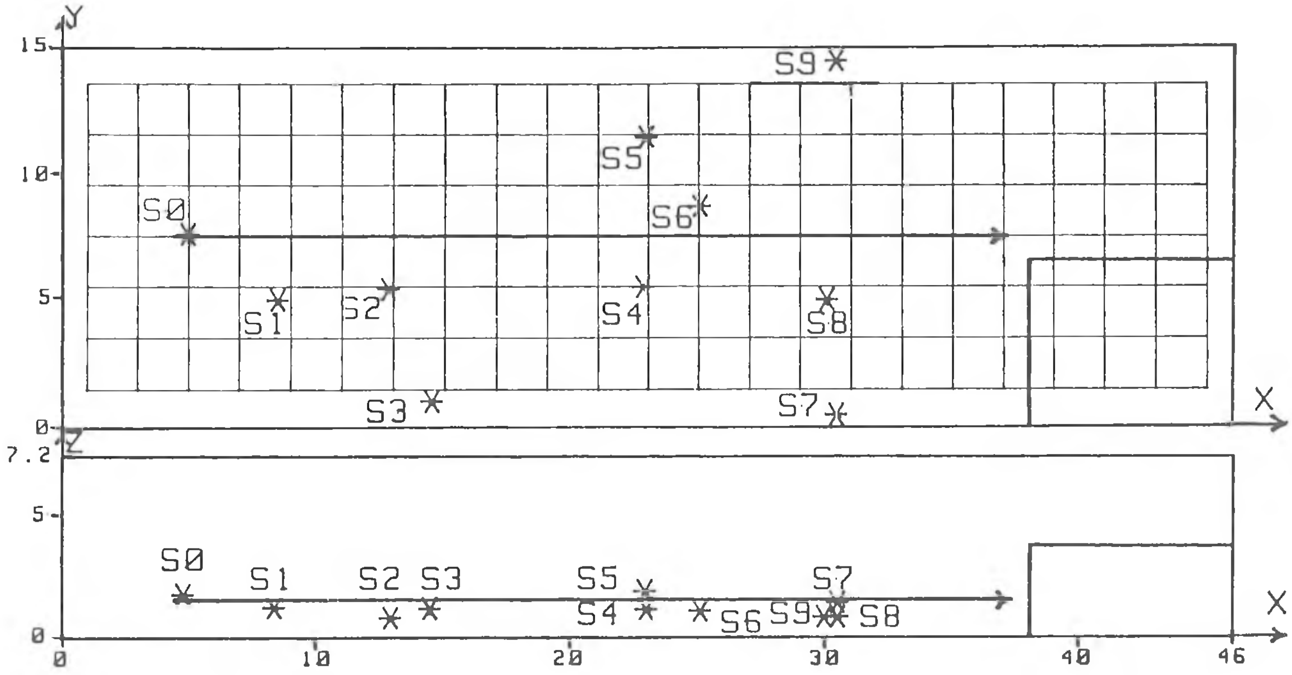

Figure 2 - Plan and section of the machine shop, showing the dimensions, source positions, receiver grid and the sound propagation measurement line (⟶).

3. THE MACHINE SHOP

Fig. 1 is a photograph of the machine shop as tested. The building, shown in plan and section in Fig. 2, is parallepipedic with dimensions of 46.3 m × 15.0 m × 7.2 m high. At one end was located a partial-height partition, separating the main machine shop from a small enclosure. The floor of the building was of concrete, its walls were of unpainted blockwork, its ceiling was of typical steel-deck construction (consisting of corrugated metal inside, insulation, a vapor barrier and gravel

Table 1 - Octave-band absorption coefficients of the machine-shop surfaces and of the air, used in all predictions

Octave band (Hz)	Surface absorption coefficient	Air absorption coefficient (Np/m)
250	0.12	0.0003
500	0.10	0.0005
1000	0.08	0.001
2000	0.06	0.003
4000	0.06	0.006

Table 2 - Description and octave-band sound power levels of the nine noise sources

N°	Name	Sound power level (dB re: 10^{-12} W) 250	500	1000	2000	4000
1.	Lathe	66.9	84.2	78.1	73.5	69.7
2.	Milling machine	79.5	86.1	87.8	84.3	78.2
3.	Radial saw	82.8	79.3	79.4	79.6	78.9
4.	Drill	75.9	78.2	81.4	78.8	68.6
5.	Band saw	77.5	74.2	72.8	71.0	68.2
6.	Grinder	78.4	80.8	77.4	72.1	70.5
7.	Dust collector	81.5	82.9	79.2	77.8	68.9
8.	Shear	82.2	80.7	78.7	74.6	64.6
9.	Sander	79.1	83.5	78.3	76.3	71.4

outside). The roof was supported by metal trusswork. The average octave-band absorption coefficients of the surfaces of industrial enclosures of this construction have previously been evaluated from measurements of the reverberation time in the nominally-empty buildings and have been found to vary little from one building to another [5]. On the basis of these results the absorption coefficients shown in Table 1 were used in all predictions. Note that all surfaces were assumed to have the same absorption; comparisons of sound propagation predictions and measurements for empty buildings have shown that excellent prediction accuracy is achieved under this assumption [6]. Air absorption values were those, also presented in Table 1, corresponding to a temperature of 25°C, a relative humidity of 80% - the conditions prevailing during the tests.

The machine shop contained many fittings distributed fairly uniformily over the floor area, though leaving two small, relatively empty open areas. They included machine tools and other equipment, work benches, cabinets and stock piles. The average fitting height was about 1.5 m.

During the sound pressure level measurements nine sources were in operation. Details of these sources are presented in Table 2; their plan positions in the machine shop are shown in Fig. 2. Note that the heights are those of the centres of gravity of the machine bodies. The 250-4000 Hz octave-band sound power levels of these sources were determined using sound-intensity techniques. A rectangular survey surface was defined around each source. The average normal sound intensity on each of the five sides of the surface was measured by continuously sweeping the intensity probe over the surface for about 2 min. Sound power levels were determined from the average intensities on the surface and from the surface area. These levels are presented in Table 2. During the intensity measurements only the machine under test was in operation. The machine tools were operated without stock; thus, the main noise sources were electric motors, gearboxes, bearings, ventilation fans and exhausts.

4. VALIDATION PROCEDURE

In order to validate the ray-tracing model in the machine shop, the following procedure was followed:

a. The machine shop was modelled with respect to its geometry, surface absorption coefficients, fitting distribution, source power, source and receiver locations and air absorption;

b. Measurements were made of the octave-band sound propagation in the factory. The sound propagation - the variation with distance from an omnidirectional point source of the sound pressure level minus the source sound power level - is the variable quantifying the influence of the enclosure on the variation of noise levels with distance from a source. In a multi-source situation the noise level at a receiver position is the energetic sum of the contributions of the various sources, each determined from the sound propagation curve for the appropriate source/receiver distance, and from the source power.

c. The sound propagation curves were predicted using the known parameter values; the unknown fitting densities and absorption coefficients were varied until a best fit with the experimental results was obtained;

d. The sound power of the sources were measured;

e. Sound pressure levels were measured at positions on a grid throughout the machine shop, with all sources operating;

f. Sound pressure levels at the grid positions were predicted using the known and best-fit parameter values;

g. Measured and predicted sound pressure levels were compared.

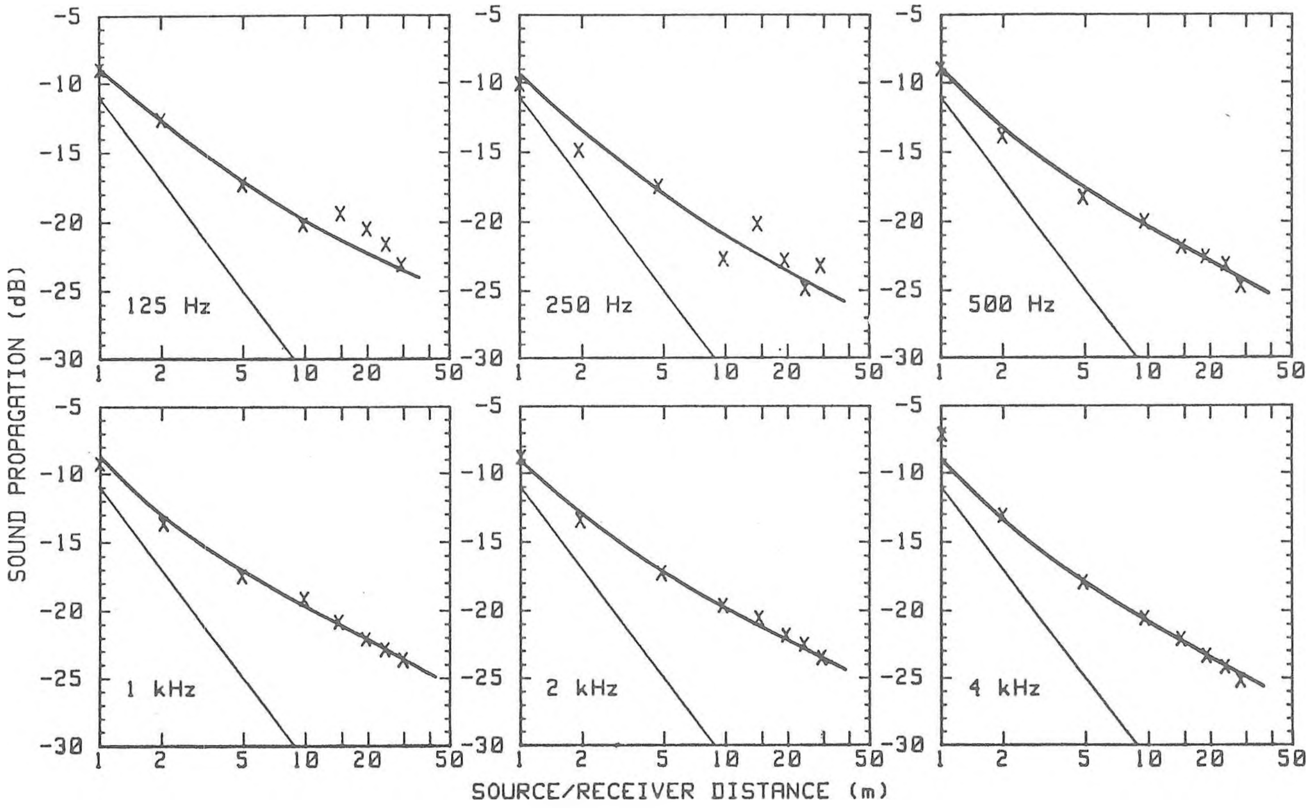

Figure 3 - Octave-band sound propagation curves for the machine shop as measured (X) and predicted (▬). Also show for reference is the free-field sound propagation (——).

5. EXPERIMENTAL DETAILS

5.1 Sound propagation

Measurements were made of the sound propagation in the machine shop, in octave bands from 250-4000 Hz. An dodecahedral loudspeaker array, consisting of 12 KEF B110-B loudspeaker units, was located at 5 m from one end wall at mid width, as shown in Fig. 2; the source height was 1.7 m. The loudspeaker array radiated omnidirectionally within 1 dB in the octave bands 250-1000 Hz and within 2 and 3 dB in the 2 and 4 kHz bands, respectively. The octave-band sound power levels of the array had been previously measured using sound-intensity techniques. With this array radiating broadband noise, octave-band sound pressure levels were measured at distances of 1, 2, 5, 10, 15, 20, 25 and 30 m from the source along the room centre line as shown in Fig. 2. The sound propagation was calculated from the octave-band sound pressure and source power levels. Fig. 3 shows the measured curves. Note that, as is always the case in real factories, no constant-level reverberant field existed far from the source - in general levels decreased with distance. At low frequencies the curves are less smooth at large distances than they are at high frequencies. While the precise explanation of these low frequency variations is not known, they can be assumed to be due to a combination of modal effects and the influence of obstacles near the measurement positions.

5.2 Sound pressure levels

Measurements were also made, with the nine noise sources in operation and in octave bands from 250-4000 Hz, of the sound pressure levels at 161 receiver positions on a 7 × 23 grid as shown in Fig. 2. The receiver positions were at 2 m centres along the two horizontal room axes, and at a height of 1.5 m. Positions within 1 m of a noise source or large obstacle were noted. Measurements were also made of the background noise levels, which were found to be more than 15 dB below the noise levels due to the machines at all positions and in all octave bands. From the measured octave-band levels, the dB(A) level was calculated. For information, Fig. 4 shows the measured dB(A) levels in the form of an iso-contour map for an inter-contour interval of 1 dB(A). Also shown in this figure are the noise source positions. Note that level peaks occur near source positions as expected. Note also that a level peak occurs at a position with coordinates of approximately $x = 5$ m, $y = 10$ m. This occured due to a high level in the 500 Hz octave band only. No sound source was near this position and no explanation, except measurement error, is known for the existence of this peak.

6. MODELLING OF THE EXPERIMENTAL CONFIGURATIONS

6.1 Sound propagation

In order to determine the effective fitting densities and absorption coefficients the sound propagation measurement configuration was modelled by ray tracing. Regarding the fitting distribution, the shop volume was divided into upper and lower sub-volumes, delimited by the horizontal plane at a height of 1.5 m, the average fitting height. On the basis of previous comparisons between sound propagation measurements in empty factories of similar construction and predictions [5], a fitting density of 0.03 m^{-1} and a fitting absorption coefficient of 0.05 were assigned to the upper region, which was essentially empty but contained a mobile crane, lighting fixtures and the roof trusswork.

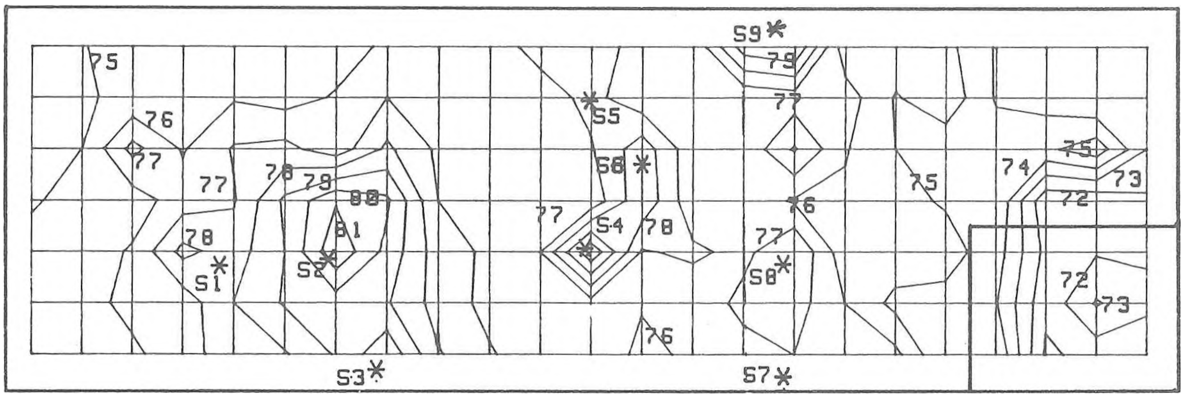

Figure 4 - Iso-contour map of dB(A) sound pressure levels measured in the machine shop

In order to determine the fitting density and absorption coefficient of the lower region, containing the main fittings, the following procedure was followed:

a. With the fitting absorption coefficient set to 0.05 [3] the fitting density was varied. While it was found possible to find a fitting density which gave good agreement with experimental results at larger distances from the source, levels at smaller source distances were always overestimated by 1-2 dB.
b. With the fitting absorption coefficient increased to 0.1 in order to decrease predicted levels at shorter source distances, the fitting density was varied until a best fit was obtained in all octave bands. Fig. 3 shows the curves predicted with the best-fit density of 0.23 m^{-1}. The agreement is excellent at all frequencies and distances. Differences of more than 1 dB occur only at large distances and low frequencies, for which significant local variation of the measured sound propagation levels occured, as previously discussed.

In summary, with the machine shop modelled as discussed above, ray-tracing models the measured octave-band sound propagation with excellent accuracy.

6.2 Sound pressure levels

With the room modelled as discussed above, and using the measured source power levels and best-fit fitting density and absorption coefficient, octave-band sound

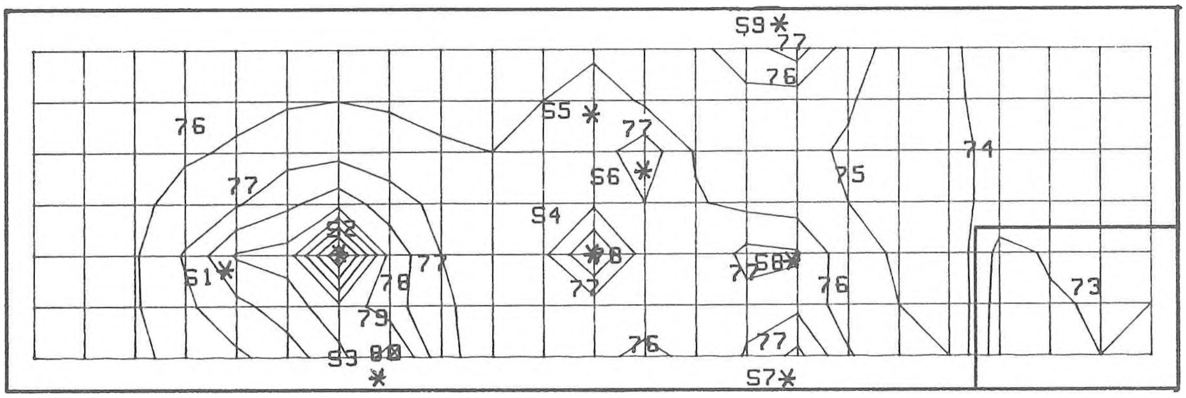

Figure 5 - Iso-contour map of dB(A) sound pressure levels in the machine shop as predicted using best-fit parameters

Table 3 - Ranges, averages and standard deviations in dB of the differences between the predicted and measured sound pressure levels at 161 grid positions in the machine shop

	Octave band (Hz)					
Quantity	250	500	1000	2000	4000	A
Minimum	-5.1	-6.8	-3.5	-1.8	-2.4	-2.9
Maximum	6.1	2.8	2.9	2.5	2.3	2.1
Average	-0.2	-1.2	0.0	0.2	0.2	-0.3
Standard deviation	1.6	1.9	0.9	0.7	0.9	0.9

pressure levels were predicted for all 161 grid position. The predicted levels correspond to the average level in a 2 m cube centred at the grid point. The octave-band levels were used to calculate dB(A) levels. As an example the predicted dB(A) iso-contour map is shown in Fig. 5.

In order to evaluate the accuracy of prediction, measured octave-band and dB(A) levels were subtracted from the corresponding predicted levels for all grid positions. The ranges, averages and standard deviations of the differences were then evaluated - these are presented in Table 3. As an example Fig. 6 shows the iso-contour map of the difference between the predicted and measured dB(A) levels, with the source positions superimposed.

With respect to these results, several observations can be made:

a. Differences between predicted and measured levels range from -7 to +6 dB at individual points, though the average differences are, in general, very small. The standard deviations are of the order of 1.5 dB at 250 and 500 Hz and 0.9 dB at higher frequencies. On average the prediction accuracy is very high.

b. Prediction accuracy is lowest at low frequency. This is probably partly due to the fact that the local variation of the sound propagation curves at low frequencies were not modelled, as discussed above. At 500 Hz the unexplained high measured level near x = 5 m, y = 10 m makes the accuracy appear artificially low.

c. As a rule, prediction overestimates levels at as many positions as it underestimates levels. In certain cases the prediction accuracy is low at positions near noise sources (eg. source 1). This is not surprising since the sources may not have been omni-directional as modelled, and since levels near sources depend highly on the exact positions of the active sources and the receiver, these not having been accurately modelled. Note however that the prediction accuracy was high for receiver positions near certain other sources (eg. source 2). Further the accuracy was, in general, no worse at positions near large obstacles than far from them.

d. In general, the prediction accuracy was lower than average at positions near the partial-height partition, both inside and outside the enclosure. Levels inside the enclosure near its short wall were underestimated at all frequencies. This can be explained by the fact that the ray-tracing model did not model diffraction over the top of the partition, this tending to increase levels in the shadow zone of the partition. Also, levels tended to be overestimated at high frequencies outside the enclosure near its long wall; the

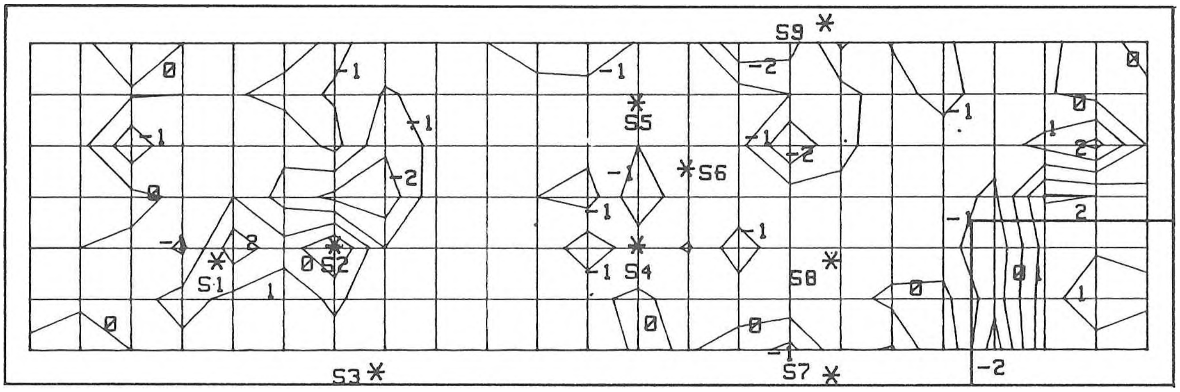

Figure 6 - Iso-contour map of the differences between the predicted and measured dB(A) sound pressure levels

reason for this is not known. Finally levels tended to be underestimated at low frequency in the relatively open region of the shop bounded by x = 33 m, x = 38 m, y = 3 m and y = 15 m. It would be reasonable to hypothesise that this underestimation can be explained by the fact that the floor of the shop was assumed to be uniformly fitted, with no open spaces, and the fact that noise levels decrease more rapidly with distance in a fitted region than in an open one. However no such undestimation occured with respect to the other open region at the centre of the machine shop.

7. CONCLUSION

Ray-tracing has been shown to predict noise levels throughout a workshop - whether close to or far from noise sources or obstacles, and in an enclosure created by a partial-height partition - with very good accuracy. The accuracy is lower than average at low frequencies than at high frequencies, probably due to modal effects. The accuracy is also low in the enclosure in the shadow zone of the partition; work is in progress to account for diffraction effects in the ray-tracing model.

While these tests were carried out for a real factory, this still represents a somewhat ideal situation. First, it was possible to estimate surface absorption coefficients from previous research. Further it was possible to measure the source powers under good conditions. More importantly, it was possible to measure the sound propagation in the existing factory when not in operation in order to estimate the fitting density. It is not yet known how to determine the factory fitting density a priori.

With the machine shop modelled with such accuracy it would, of course, be possible to investigate the efficacy of noise control measures such as surface absorbent treatments and acoustic screens.

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Directeur général
FAX:
(514)453-0554