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Résumé

Les modèles de prévision du bruit en usine ont une valeur inestimable pour l'évaluation des niveaux d'exposition des travailleurs au bruit avant la construction et, si nécessaire, pour l'évaluation des modifications à apporter et des mesures de réduction du bruit à prendre. Les techniques de traçage des rayons se sont révélées un outil offrant la précision et la souplesse nécessaires. Pour évaluer la précision d'un modèle de traçage des rayons, on a fait des comparaisons entre les niveaux de pression acoustique prévus et les niveaux mesurés dans le cas d'un atelier comportant neuf sources de bruit actives. La modélisation de l'atelier a été réalisée à partir de la géométrie connue, de l'emplacement des sources et des récepteurs, des coefficients d'absorption de l'air, et des niveaux de puissance acoustique mesurés des sources. Le choix des coefficients d'absorption des surfaces était basé sur des mesures de temps de réverbération dans des usines semblables vides. On a choisi la densité d'ajustement et les coefficients d'absorption de l'atelier en se basant sur des travaux de recherche précédents et sur une comparaison des courbes de propagation du son prévues avec les courbes établies à partir de mesures pour l'atelier, en faisant varier la densité d'ajustement en vue d'obtenir l'ajustement optimal. Le modèle de traçage des rayons a donné des prévisions d'une grande précision. Par comparaison, les prévisions basées sur la théorie d'Eyring sont moins précises. Enfin, l'utilité et la souplesse de la méthode de traçage des rayons sont démontrées par la prévision de l'efficacité des mesures possibles de réduction du bruit, notamment l'utilisation d'écrans acoustiques et de dispositifs d'absorption suspendus.

Case History: Factory Noise Prediction Using Ray Tracing—Experimental Validation and the Effectiveness of Noise Control Measures*

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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 modeled 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 coefficients 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 excellent prediction accuracy. By comparison, predictions by the Eyring theory are shown to be less accurate. Finally, the usefulness and flexibility of the ray-tracing approach are demonstrated by predicting the effectiveness of possible noise control measures comprising acoustic screens and suspended absorption.

Accurate methods for modeling and predicting noise levels in factories are invaluable in the planning of factory buildings, equipment layouts, and potential noise control measures. They permit worker noise-exposure levels to be estimated before the factory is built and its equipment purchased. If predictions indicate that noise levels will exceed admissible limits, the factory building and/or equipment and worker locations can be modified. Furthermore, 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 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 accounts neither for the presence of room contents, which have been shown to modify factory sound fields significantly, nor for the exact room shape and the distribution of surface absorption.[2] Existing empirical formulae approximate the sound propagation curve inaccurately and provide limited frequency information. The 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 content 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 any other model in an idealized situation does not guarantee the accuracy of predictions made for real factories. This is partly because real factories do not have, for example, rectangular obstacles. Furthermore, whereas the relevant values of certain parameters—such as the geometry, source power, source and receiver locations—can be estimated *a priori* with good accuracy, it is not yet known how to determine accurately the values of other parameters, such as the surface absorption coefficients and the obstacle density.

The objective of the study reported here was to validate further 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. The model was then used to investigate possible noise control measures, in order to demonstrate its usefulness and flexibility.

The Ray-Tracing Model

The ray-tracing model used in this work was developed by the INRS in France and modified by the author. Full details of this model are published elsewhere and only a brief description is given here.[4] 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 distances between the centers of pairs of the fittings, which scatter omni-directionally, are 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 a fitting 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 modeled.

Briefly, the ray-tracing procedure is 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 30 minutes.

The Machine Shop

Figure 1 is a photograph of the machine shop as tested. The building, shown in plan and section in Fig. 2, is parallelepipedic with dimensions of 46.0 × 15.0 × 7.2 m. 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, and its ceiling was of typical steel-deck construction (consisting of corrugated metal inside, insulation, a vapor barrier and gravel outside). The roof was supported by metal trusswork. The average octave-band absorption coefficients of the surfaces of industrial enclosures of this construction were estimated from previous 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 "empty room" absorption coefficients shown in Table 1 were used in all predictions. That the

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

absorption coefficient tends to decrease with increasing frequency might surprise some readers. In fact, however, this is quite normal in buildings with suspended-panel roofs; the relatively high absorption at low frequencies is due to their vibration and transmission characteristics.[2,6] 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 using these absorption coefficients and this assumption.[7] Air absorption values also presented in Table 1 were those corresponding to a temperature of 25°C and a relative humidity of 80 percent, the conditions prevailing during the tests.

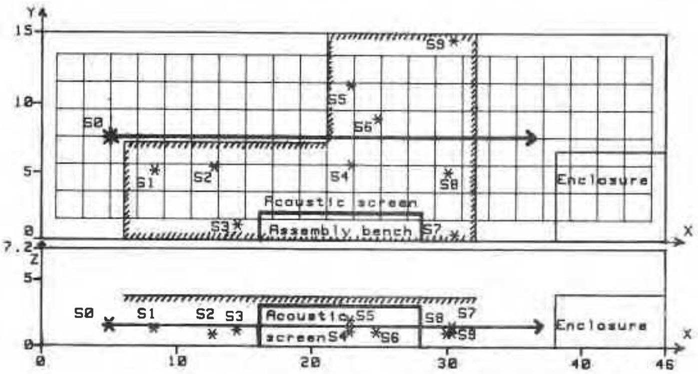


Figure 2—Plan and section of the machine shop, showing its dimensions, source positions, receiver grid, and the sound propagation measurement line (⟶). Also shown is the enclosure, assembly bench and acoustic screen, and the limit of the suspended baffles (///////). All dimensions are in metres

TABLE 1
OCTAVE-BAND ABSORPTION COEFFICIENTS OF THE AIR AND OF THE MACHINE-SHOP SURFACES USED IN THE PREDICTIONS

Octave band (Hz)	"Empty room" surface absorption coefficient	Air absorption coefficient (Np/m)	"Fitted room" surface absorption coefficient	Screen absorption coefficient	Suspended baffle absorption coefficient
250	0.12	0.0003	0.21	0.30	0.40
500	0.10	0.0005	0.18	0.50	0.70
1000	0.08	0.001	0.15	0.70	0.80
2000	0.06	0.003	0.14	0.85	0.85
4000	0.06	0.006	0.14	0.90	0.90

TABLE 2
DESCRIPTION AND OCTAVE-BAND SOUND POWER LEVELS OF THE NINE NOISE SOURCES

No.	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

The machine shop contained many fittings distributed fairly uniformly over the floor area, though leaving two small, relatively empty open areas. The fittings 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 noise sources were in operation. Details of these sources are presented in Table 2; their positions in the machine shop are shown in Fig. 2. Note that the positions are those of the centers of gravity of the machine bodies. The 250 to 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 minutes. Sound power levels were determined from the average intensities on the surface and from the surface areas. 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.

Validation Procedure

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

a. The machine shop was modeled 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 SP(r) is the variation with distance (r) from an omni-directional point source of the sound pressure level L_p (r) minus the source sound power level, L_w; that is, SP (r) = $L_p(r) - L_w$. It is the variable quantifying the influence of the enclosure on the variation of noise level 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 powers of the nine sources were measured;
e. Sound pressure levels were measured at positions on a grid throughout the machine shop, with all the nine 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.

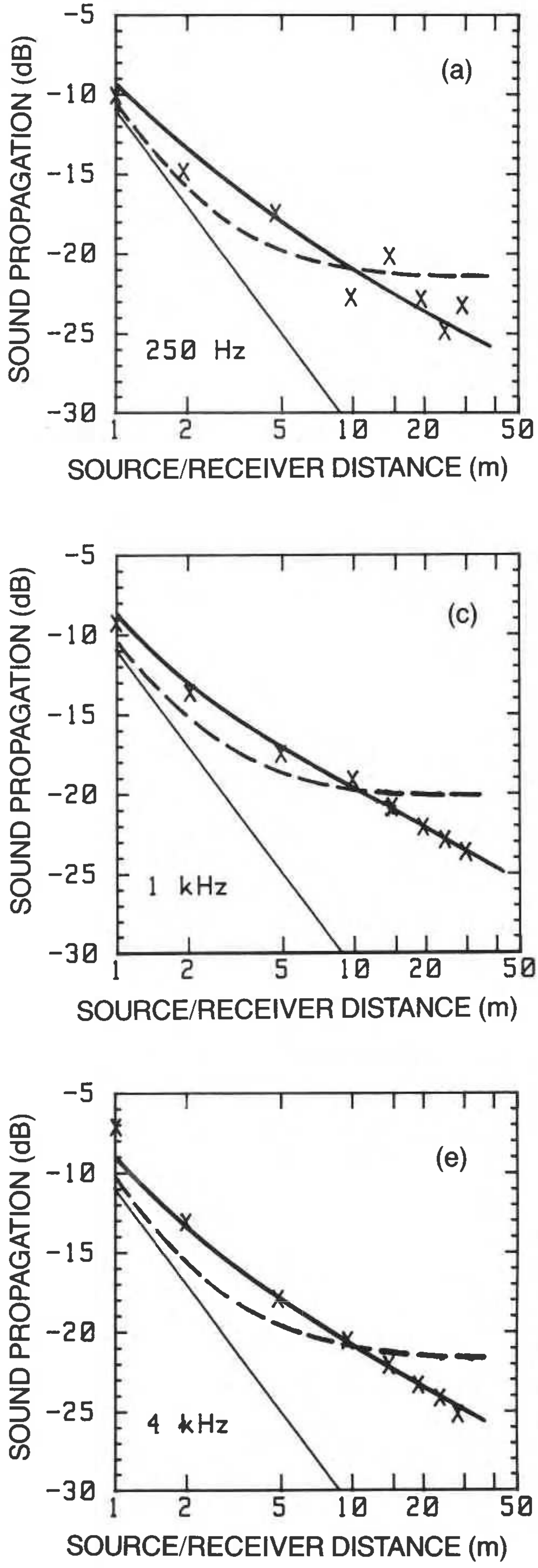
Experimental Details

Sound Propagation. Measurements of the sound propagation were made in the machine shop, in octave bands from 250 to 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 is shown in Fig. 2; the source height was 1.7 m. The loudspeaker array radiated omni-directionally within 1 dB in the octave bands 250 to 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 center line as shown in Fig. 2. The sound propagation was calculated from the octave-band sound pressure and source power levels. Figure 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 for 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.

Sound Pressure Levels. Measurements were also made, with the nine noise sources in operation and in octave bands from 250 to 4000 Hz, of the sound pressure levels at 161 receiver positions on a 7 $\times$ 23 grid as shown in Fig. 2. The receiver positions were at 2 m centers 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 A-weighted level was calculated. Figure 4 shows the measured A-weighted levels in the form of an iso-contour map. 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 occurred due to a high level in the 500 Hz octave band. No sound source was near this position and no explanation, except measurement error, is known for the existence of this peak.

Modeling the Experimental Configurations

Sound Propagation. In order to determine the effective fitting densities and absorption coefficients, the sound propagation measurement configuration was modeled by ray trac-



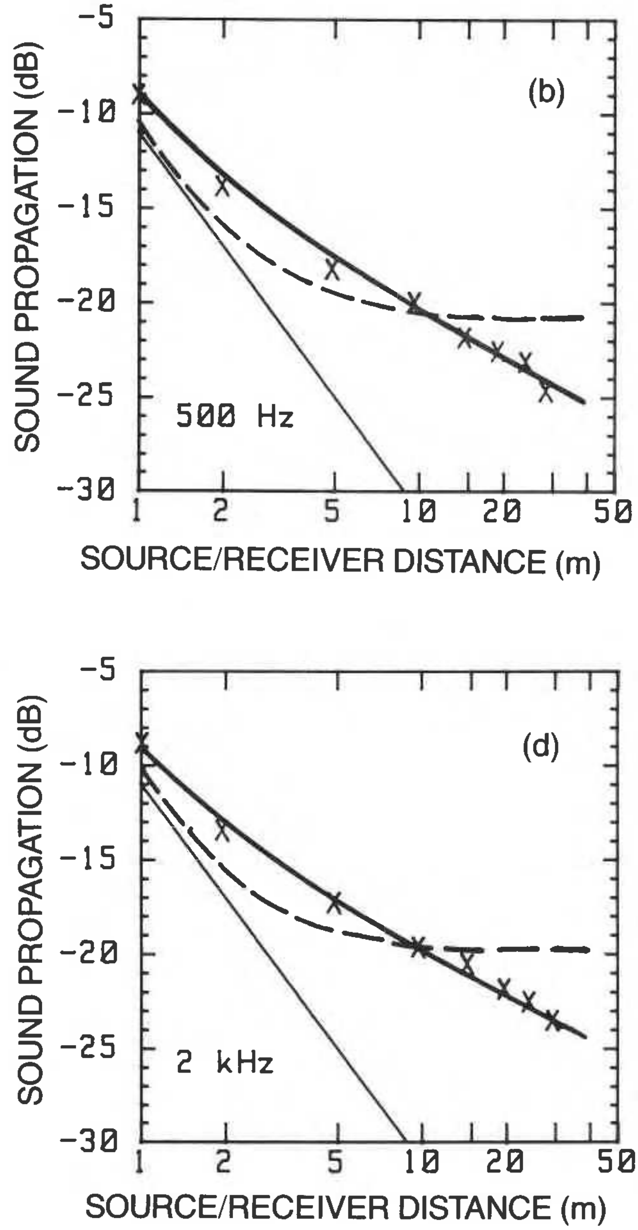


Figure 3a-e—Octave-band sound propagation curves for the machine shop as measured (X) and as predicted by ray tracing (——) and the Eyring theory (— —). Also shown for reference is the free-field sound propagation (———)

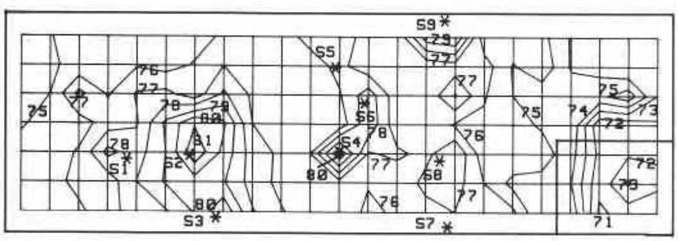


Figure 4—Iso-contour map of the A-weighted sound pressure levels measured in the machine shop

ing. 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.

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

a. With the fitting absorption coefficient set to 0.05, 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 to 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. Figure 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 occurred, as was previously discussed. In summary, with the machine shop modeled as discussed, ray tracing models the measured octave-band sound propagation with excellent accuracy.

Sound Pressure Levels. With the room modeled as discussed above, and using the measured source power levels and best-fit fitting density and absorption coefficient, octave-band sound pressure levels were predicted for all 161 grid positions. The predicted levels correspond to the average level in a 2-m cube centered at the grid point. The octave-band levels were used to calculate the A-weighted levels. As an example, the predicted A-weighted iso-contour map is shown in Fig. 5.

In order to evaluate the accuracy of prediction, measured octave-band and A-weighted 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 A-weighted 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 modeled, 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 (e.g., source 9). This is not surprising since the sources may not have been omni-directional as modeled, and since levels near sources depend highly on the exact positions of the active sources and the receiver, and these may not have been accurately modeled. Note, however, that the prediction accuracy is high for receiver positions near certain other sources (e.g., source 8). Furthermore, the accuracy is, in general, no worse at positions near large obstacles than far from them.

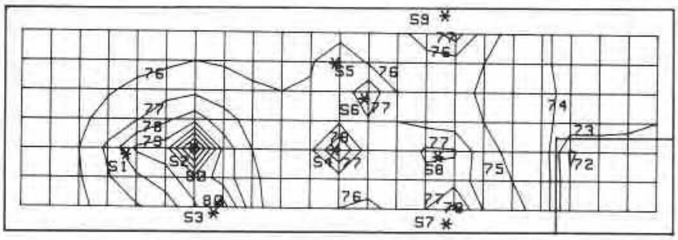


Figure 5—Iso-contour map of the A-weighted sound pressure levels in the machine shop as predicted by ray-tracing using the best-fit parameters

TABLE 3
RANGES, AVERAGES AND STANDARD DEVIATIONS IN dB OF THE DIFFERENCES BETWEEN THE SOUND PRESSURE LEVELS AT 161 GRID POSITIONS IN THE MACHINE SHOP AS PREDICTED BY RAY TRACING AND AS MEASURED

Quantity	Octave band (Hz)					A
	250	500	1000	2000	4000	
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

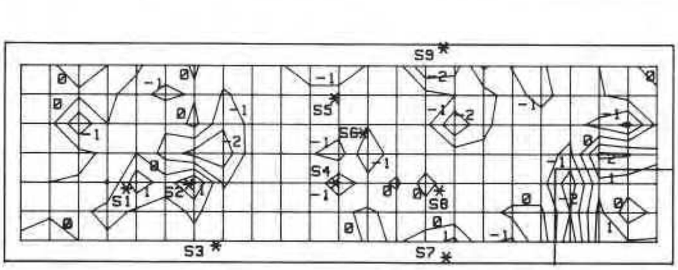


Figure 6—Iso-contour map of the difference between the A-weighted sound pressure levels predicted by ray-tracing and those measured

d. In general, the prediction accuracy is 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, thus 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 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 hypothesize 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 underestimation occurred with respect to the other open region near the center of the machine shop.

Further Investigations

Despite research clearly demonstrating its inapplicability, the Sabine/Eyring theory is still often used to predict noise levels in factories.[7] Thus, it is of interest to evaluate its accuracy with respect to the machine shop. A fundamental problem is that of how to account for the influences of the machine shop fittings on the sound field, since the Sabine/Eyring theory does not specifically incorporate this parameter.[2] One alternative would be to reduce the room volume and increase the surface absorption according to the estimated volumes, surface areas, and the absorption coefficients of the fittings. However, a second but rather equivalent approach was taken here. At the time of the sound propagation measurements, the octave-band reverberation times were also measured. From these, the "empty room" dimensions, the air absorption coefficients, and the average surface absorption coefficients were determined using the Eyring formula. These "fitted room" coefficients are presented in Table 1; they are significantly higher than the corresponding "empty room" values, since fittings reduce reverberation times, apparently increasing the surface absorption.[2]

Figure 3 shows the sound propagation curves predicted by the Eyring theory using the "fitted room" coefficients. Clearly the agreement with the measured curves is poor. Levels at distances within about 10 m of the source are underestimated; those at larger distances are overestimated. This can be explained by the disproportionate shape of the workshop and the fact that fittings redistribute sound energy towards the source due to backscattering.[2,7]

Figure 7 shows the contour map of the A-weighted sound pressure levels predicted by the Eyring theory as described. Figure 8 shows the contour map of the differences between these levels and those measured. Table 4 presents the relevant statistics related to these differences and those in octave bands. From Fig. 8 it can be seen that the Eyring theory tends to underestimate levels in the region of the noise sources—that is, at positions within about 10 m of a source—and to overestimate levels at positions far from all sources. This is as expected from the sound propagation results. Notice that levels inside the enclosure are particularly overestimated since the Eyring theory did not account for barrier attenuation. Comparison of Tables 3 and 4 shows that the Eyring prediction is significantly less accurate than ray-tracing prediction, especially at mid and high frequencies and in A-weighted decibels.

It is of considerable interest to turn our thoughts to another important matter—that of the *a priori* estimation of the factory fitting density. As mentioned, no proven method exists as yet for accurately determining this quantity. According to Jovivic, the average fitting density in a region can be estimated approximately as the total fitting surface area divided by four times the volume of the region.[8] A glance at Fig. 1 will convince the reader that the total surface area of factory fittings is not easy to estimate. One possibility would be to calculate the surface area of the fictitious rectangular boxes that would just fit over the main parts of the fittings. This has been done for the lower region of the machine shop; the resulting density is 0.16 m^{-1}. The density found by the best fit procedure is 44 percent higher than the estimated value. While no firm conclusions can be drawn from a single case, it should be noted that similar comparisons by other researchers have found similar differences between the estimated and effective values.[9]

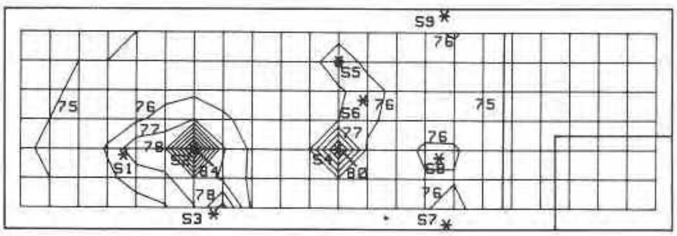


Figure 7—Iso-contour map of the A-weighted sound pressure levels in the machine shop as predicted by the Eyring theory using the "fitted-room" absorption coefficients

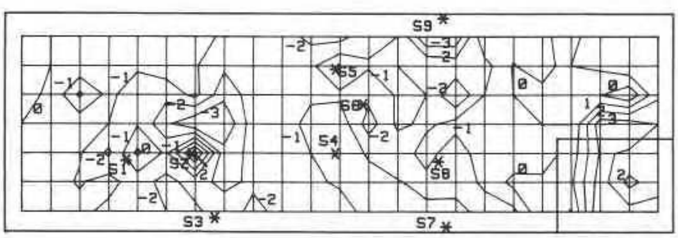


Figure 8—Iso-contour map of the difference between the A-weighted sound pressure levels predicted by the Eyring theory and those measured

Table 4
Ranges, Averages, and Standard Deviations in dB of the Differences between the Sound Pressure Levels at 161 Grid Positions in the Machine Shop as Predicted by the Eyring Theory and as Measured.

Quantity	Octave band (Hz)					A
	250	500	1000	2000	4000	
Minimum	−4.5	−7.6	−4.8	−3.0	−4.0	−4.0
Maximum	5.2	4.1	4.3	3.7	5.1	4.0
Average	−0.5	−1.5	−0.1	−0.2	0.3	−0.6
Standard deviation	1.7	2.1	1.7	1.4	1.7	1.5

Effectiveness of Noise Control Measures

Though typical noise levels in the workshop did not, in fact, warrant it, it was of interest to use the ray-tracing model to investigate the effectiveness of possible noise control measures, in order to demonstrate the usefulness and flexibility of the model. The workshop typically contained twenty workers. They operated machine tools and performed other tasks, such as parts assembly. Obviously, when operating machines the workers tended to stand close to noise sources. However, at other times they would find themselves more or less close to noise sources. In particular, assembly operations took place at a long bench, shown in Figs. 1 (center, right side) and 2. Since these benches are surrounded by noise sources, workers undertaking quiet assembly operations were unnecessarily submitted to high noise levels. It is relevant to consider how best to reduce noise levels throughout the machine shop and, in particular, at the assembly bench. An obvious means for reducing noise levels at the assembly bench is by the installation of a three-sided screen, surrounding the bench. On the other hand, noise levels throughout the shop could be reduced, with restrictions on movement around the shop minimized, by locating acoustically absorptive materials in the void above the machines, assembly bench, and workers. This could involve complete or partial treatment of the factory ceiling or, at least in principle, the suspension of such materials immediately above the fitted zone. Without considering the practicality of such measures, we have used the ray-tracing model to predict the reduction of sound pressure levels at the 161 grid positions, resulting from the following treatments:

1. Erection of a 3-m high, three-sided screen around the assembly bench as shown in Fig. 2. With the exception of the outer sides of the two short walls, the surfaces were assumed to be non-absorptive. The other two sides were assumed to be treated with 50-mm thick mineral wool, in order that reflections from their surfaces not increase noise levels for the operators of sources S3 and S7 located next to the screen. The screen absorption coefficients are given in Table 1.
2. In addition to the screen, a flat, horizontal layer of absorbent material was assumed to be suspended immediately below the complete machine shop ceiling (area = 690 m^2). The absorption coefficients of this treatment were assumed to be as shown in Table 1.
3. In addition to the screen, and instead of the added treatment detailed above, the absorbent layer was suspended from the ceiling at a height of 3.5 m over a region of the machine shop including the assembly bench and all nine sound sources, as is shown in Fig. 2 (area = 207 m^2).

Figure 9 shows the iso-contour map of the noise reduction in A-weighted decibels resulting from installation of the acoustic screen. Note that the predicted reductions of 1 to 2 dB may be overestimates since, as mentioned, the ray-tracing model does not include diffraction phenomena. Figure 10 shows the corresponding contour map for treatment 2. Noise levels are reduced at all positions. The reduction is greatest at the assembly bench (at least 7 dB), inside the partial height enclosure (around 10 dB) and far from all noise sources (up to 9 dB). As expected, the reduction is least in the region of the machines (as little as 0.5 dB). Figure 11 shows the results for treatment 3. With respect to treatment 2, this treatment is more effective (by about 2 dB) at the assembly bench, is less effective (by at least 4 dB) far from the sources and is equally effective in the region of the sources. Given that they would be about one half as expensive to install, suspending baffles above the machines over part of the ceiling area could be an interesting alternative.

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.

For comparison, predictions have also been made by the Eyring theory. This theory significantly underestimates sound propagation levels at shorter source/receiver distances and overestimates them at larger distances. As a result, noise levels in the workshop were underestimated by several decibels at positions near the sound sources and were overestimated far from the sources.

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. Furthermore, 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 it was not in operation in order to estimate the fitting density. It is not yet known how to determine the factory fitting density *a priori*. In this case, the apparent effective density was about 40 percent greater than that derived from the surface area of rectangular fittings of the same major dimensions as those in the shop.

In order to demonstrate the usefulness and flexibility of the ray-tracing approach, predictions were made of the effectiveness of several noise control measures. An acoustic screen around an assembly bench reduced A-weighted noise levels by 1 to 2 dB. Making the shop ceiling acoustically absorptive reduced levels at all positions, especially at positions far from the noise sources. An alternative and less expensive treatment—that of suspending baffles immediately above part of the shop—further reduced levels at the assembly bench, but was less effective than the absorbent ceiling far from the sources.

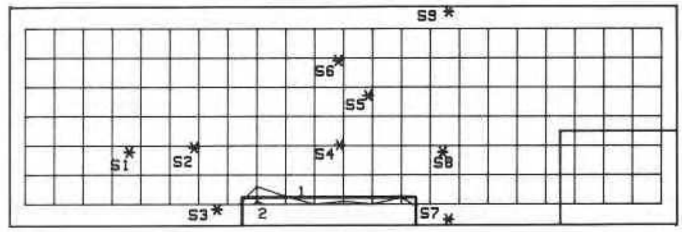


Figure 9—Iso-contour map of the reduction of sound pressure level in the machine shop due to the acoustic screen (Treatment 1)

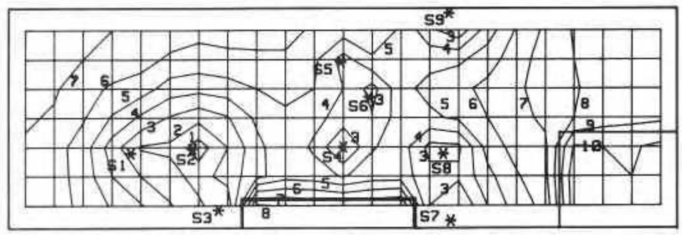


Figure 10—Iso-contour map of the reduction of sound pressure level in the machine shop due to the acoustic screen and full ceiling absorption (Treatment 2)

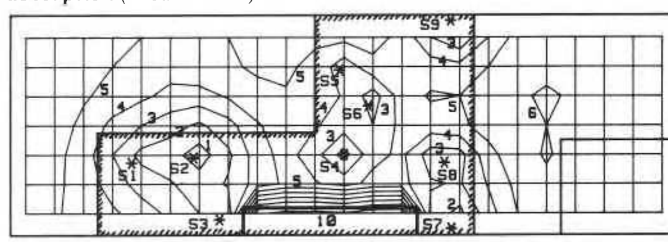


Figure 11—Iso-contour map of the reduction of sound pressure level in the machine shop due to the acoustic screen and partial suspended absorption (Treatment 3)

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