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COMPUTER PREDICTION OF SOUND PROPAGATION IN ENCLOSED SPACES USING A PRESSURE BASED MODEL.

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ABSTRACT

Previous researchers have all found abnormal sound fields in empty enclosed spaces. The sound appeared to propagate in such a way as to increase in level with increasing distance from the sound source, although it returned to its expected level at the farthest distances. These anomalies were caused by interference, which was dependent on phase shifts.

A computer model, PHASE, was previously used to predict interference effects at two frequencies in two spaces. The model has been optimised, extended and modified to predict across the full frequency range efficiently. To validate the model sound levels in a chamber fitted with absorptive material on all surfaces, as measured by Hodgson, were predicted at both a low and a high frequency. In addition the overall sound levels were predicted in an empty factory space to illustrate the accuracy of the model for practical purposes. To this end the predictions of an intensity based model, CISM, were used as a comparison.

INTRODUCTION

In the past computer prediction models[1,2,3] have been based on an intensity method of simplifying the problem by assuming that the sound source is incoherent and hence interference effects do not occur as is usually the case. However, many independent researchers have found abnormal sound fields in empty enclosed spaces [4,5,6,7]. The sound appears to propagate in such a way as to increase in level with increasing distance from the sound source, although it returns to its "correct" level at the farthest distances. These independently measured anomalies were caused by interference effects which can destructively and constructively, dependent on phase shifts, decrease or increase the sound levels in a room.

A computer model, PHASE, previously used to predict interference effects in two configurations of a laboratory space has been optimised, extended and modified to predict efficiently in a full range of frequencies [8]. PHASE was used to predict the sound propagation in two spaces: a physical scale model of a chamber and a factory space. For comparison the predictions of CISM, an intensity based image-source model have been included [9].

THE PHASE MODEL

PHASE is based on the image-source method of modelling using the parallelepiped implementation. The approximations used in the previous version of PHASE [8] have been removed at the expense of increased run-time. The approximations included grouping the frequencies into ranges of ten hertz and changing the phase relation by intervals of ten degrees. The removal of these approximations resulted in a greatly increased run-time; this was especially true when overall sound levels were predicted in linear dB. However, the model is now capable of reflecting the fine detail of modal effects in rooms. The sound pressure level, L, for a single sound source and a single receiver point, is given by:

$$L = 20lg \sqrt{\sum_{f=\frac{f}{\sqrt{2}}}^{f*\sqrt{2}} \sum_{\theta=0}^{360} \left\{ \sum_{i}\sum_{j}\sum_{k} \frac{\sqrt{c\rho \frac{W}{4\pi r^2}}}{d_{i,j,k}} * \cos\left(\frac{2\pi\theta}{360} - \frac{2\pi f}{c} d_{i,j,k}\right) * R \right\}^2 * \frac{1}{360}}$$

$$+ 10lg\left(\frac{W}{10^{-12}}\right) - 10lg\left(f * \sqrt{2} - \frac{f}{\sqrt{2}}\right), where\ i+j+k \leq n$$

where f is the octave band mid-frequency, θ is the phase difference between the direct and the reflected sound, c is the speed of sound in air, ρ is the density of air, W is the sound power of the source, r is the direct distance from the source to receiver, d is the actual distance travelled by the reflected sound wave, n is the reflection order and R is the reflection coefficient at the given frequency for the given sound path.

The model can represent an empty parallelepiped shaped space with individual absorption coefficients for each room surface. Only one directional sound source can be modelled, but any number of arbitrary positioned receivers can be represented. All predictions used an energy discontinuity of 99% [10], up to a limit of 42 reflections, due to the increased run-time.

THE ENCLOSED SPACES

Two types of space were measured in the investigation, across a wide frequency range: a physical scale model of a chamber measured in the full scale third-octave bands 200 Hz and 2 kHz, 4 kHz, 5 kHz, 6.3 kHz, 8 kHz and 10 kHz by Hodgson[7]; and an empty factory space measured by Jones[6] in eight octave bands, 63 Hz to 8 kHz, plus linear dB.

THE CHAMBER

The test room was designed to be as diffuse as possible, with a cubic shape and a uniform distribution of absorption. The room was built to a scale of 1:2.5 with dimensions, 3.17 m, 2.60 m and 1.95 m. All the room surfaces were constructed of dense concrete with 13.5 mm thick semi-rigid glass-fibre panels installed on each of the six surfaces. The absorption coefficients of the material were based on measurements in the chamber and calculated using the Eyring formula. The compact sound source was positioned in one corner of the room at a height of 1.05 m and measurements were taken at eight receivers positions at a height of 1.05 m, see Figure 1.

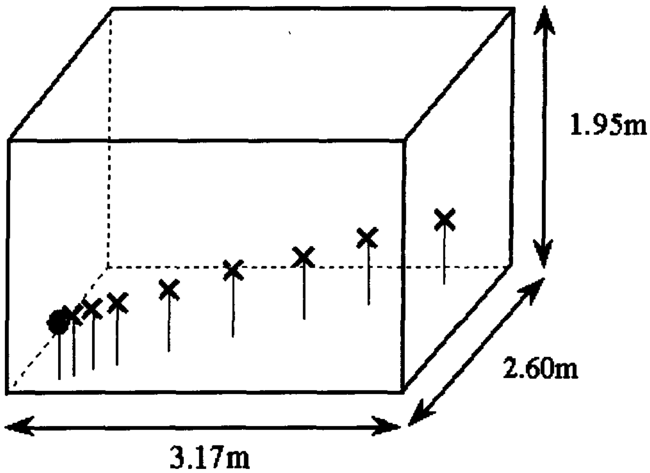


Figure 1. Source and receiver positions in a reverberation chamber

THE FACTORY SPACE

The empty factory was 56m long and 36m wide with a pitched roof of height 8.6m rising to 10.6m at the apex. The floor was concrete, the walls were brick and the roof was formed of galvanised steel backed on to mineral wool with a perforated steel lining. The absorption coefficients and hence the reflection coefficients for the building materials were obtained from standard texts. A single sound source, a Bruel and Kjaer type 4224, positioned in one corner of the space on the floor was used for the measurements, which were taken at a height of 1.5m along the length of the shop floor, see Figure 2.

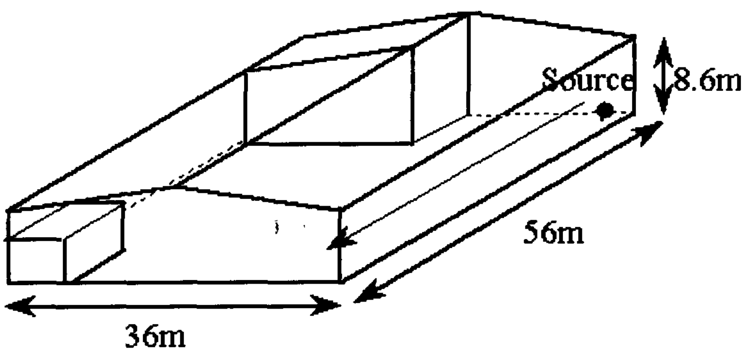


Figure 2. Source and measurement positions in the factory space.

THE PREDICTIONS

For the absorptive chamber predictions only the 200 Hz and 4 kHz results have been included for reasons of brevity. However, all the octave band results have been included for the factory space so that the practical application of the model can be clearly demonstrated. In addition to

PHASE, the CISM model was also used to predict the sound propagation in both spaces. All figures show the measured (—), CISM (····) and PHASE (----) sound levels.

THE CHAMBER PREDICTIONS

Figures 3 and 4 show the measured and predicted sound levels at 200 Hz and 4 kHz (full scale) in the absorptive chamber.

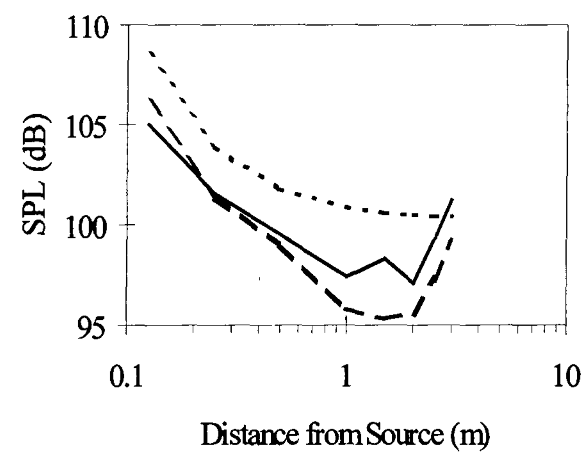


Figure 3. Chamber sound levels at 200 Hz.

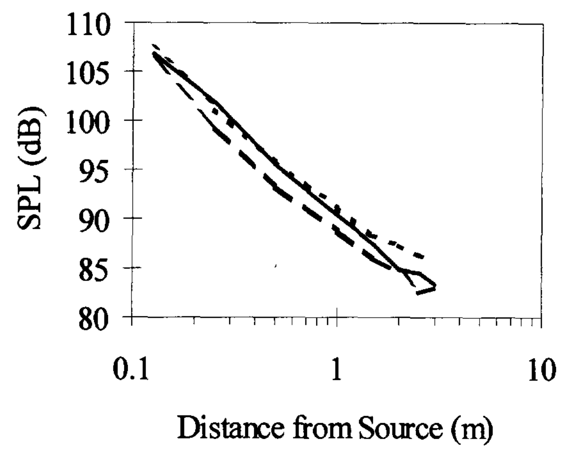
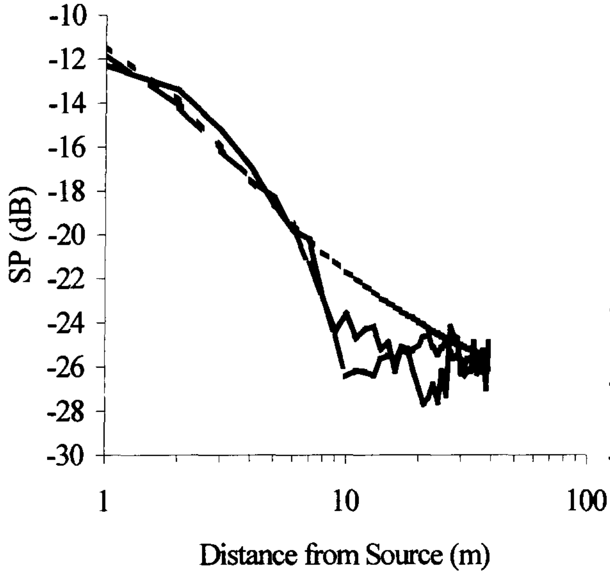


Figure 4. Chamber sound levels at 4 kHz.

The measurements at the low frequency clearly demonstrate the interference effects in this small space, see Figure 3. PHASE predicted the shape of the sound propagation curve and the absolute sound level accurately for both the frequencies. However, CISM predicted the shape and level poorly, at the low frequency, except at the furthest receiver, but was accurate at the high frequency, see Figure 4. These results confirm that interference was the cause of the unusual sound propagation, which of course could not be predicted by a pure intensity model such as CISM.

THE FACTORY SPACE PREDICTIONS

The factory space was modelled using a simplified representation of the actual geometry of the space i.e. no pitched roof and no internal walls. However, the nearest room surfaces to the source are the most significant, and the total volume and proportions of the room were modelled accurately. The results for alternate octave bands, which are representative of all the octave bands predicted are presented together with the overall sound level in linear dB, see Figures 5 to 9.



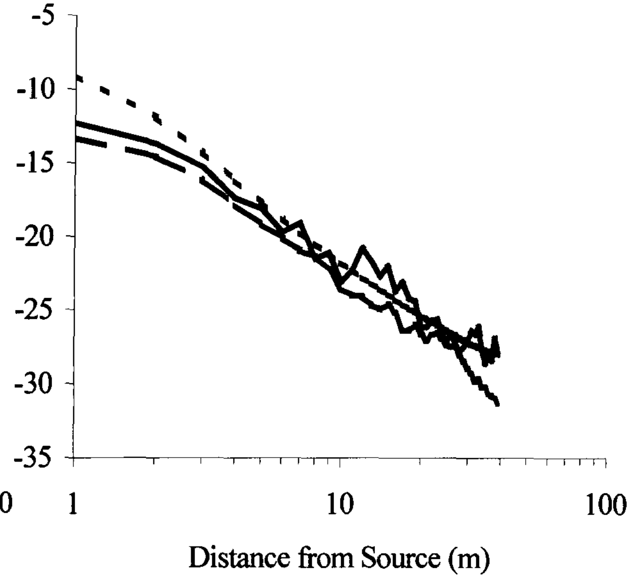
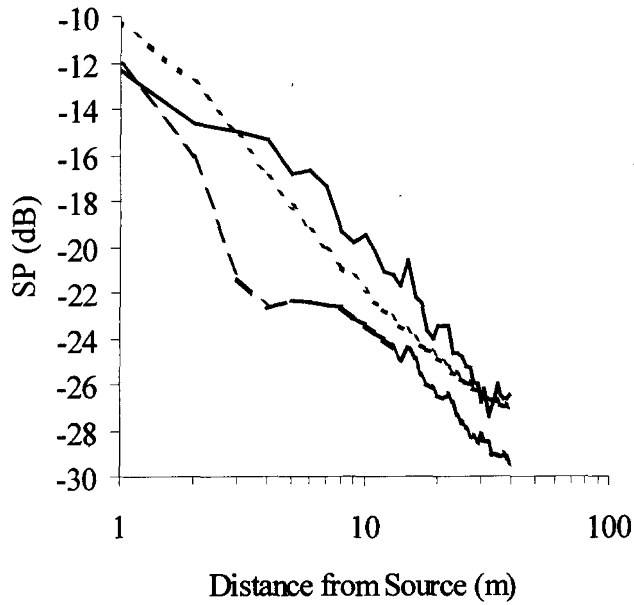


Figure 5. Factory SP, 63 Hz octave band.

Figure 6. Factory SP, 250 Hz octave band



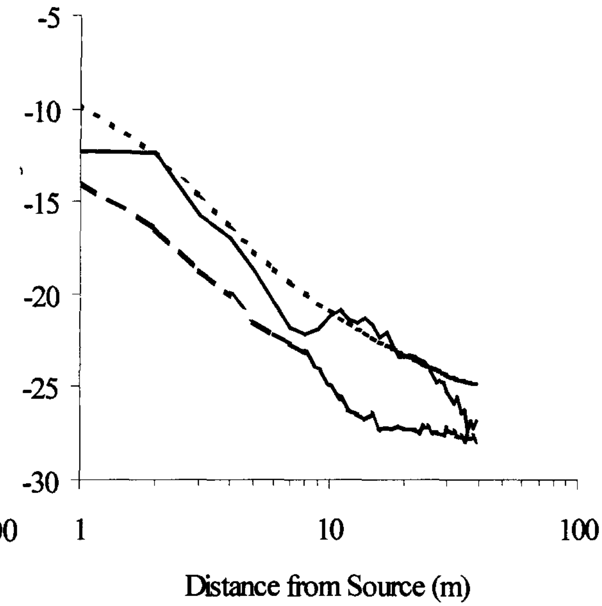


Figure 7. Factory SP, 1 kHz octave band.

Figure 8. Factory SP, 4 kHz octave band.

Table 1 shows the average prediction differences for the eight octave bands to demonstrate the overall prediction accuracy of PHASE compared to that of CISM. It can be clearly seen that PHASE is approximately as accurate as CISM with predictions within 2 dB of those measured, except for 500 Hz where the sound power level was incorrectly determined from the measurements and hence the 4 dB average error for both CISM and PHASE.

Table 1 Average Prediction Difference (dB) in the Factory Space.

	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	linear
PHASE	2.0	1.9	0.9	4.6	1.5	1.0	1.4	1.5	1.0
CISM	1.5	2.3	0.8	4.2	1.2	1.6	0.9	0.4	0.9

63 Hz Predictions. PHASE predicted the shape of the SP accurately, including the dip at 7 m from the sound source with a flattening of the curve beyond 10m, caused by the destructive interference of the direct and reflected sound from the two nearest surfaces. CISM predicted the sound levels accurately at the nearest and furthest receiver positions from the sound source, Figure 5, but with a monotonic decrease giving an average prediction difference of 1.5 dB, as compared to 2.0 dB for PHASE.

250 Hz Predictions. The measured SP curve was more consistent for this octave band than for the lower frequencies and this was accurately predicted by PHASE, the CISM model again predicting a monotonic slope, Figure 6. The result was an average prediction difference of 0.9 dB and 0.8 dB for PHASE and CISM, respectively.

1 kHz Predictions. The measured sound levels show that there was constructive interference occurring between 2 m and 7 m which was predicted as destructive interference by PHASE over precisely the same range. For the receivers beyond 7 m the relative sound levels were accurately predicted by PHASE, but with a 3 dB offset, see Figure 7. CISM correctly predicted the gradient of the slope producing a 1.2 dB average error compared to 1.5 dB for PHASE.

4 kHz Predictions. As for the 1 kHz predictions PHASE predicted a destructive interference effect when a constructive interference effect was measured, from 8 m to 20 m, see Figure 8. CISM predicted a smoothed version of the measured SP curve and hence produced an average error of 0.9 dB compared to 1.4 dB for PHASE.

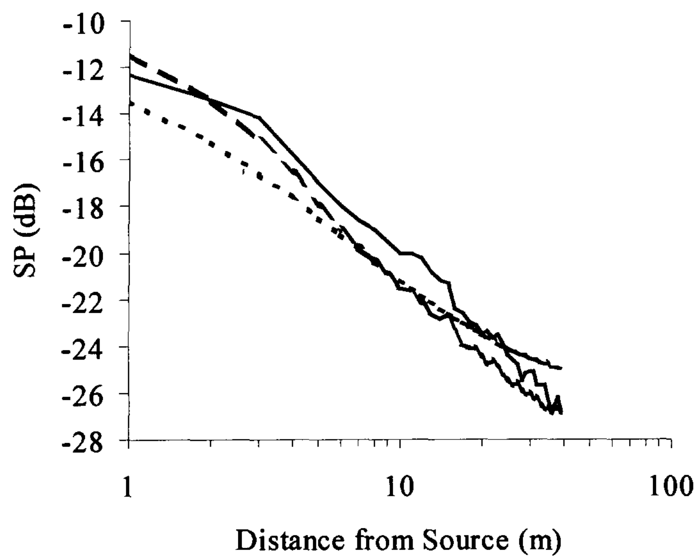


Figure 9. Factory sound propagation in linear dB.

Linear Predictions. CISM predicted the flattened SP slope in the factory, a classic image-source prediction, see Figure 9. PHASE produced sound levels similar to those measured for all the receiver positions, giving an average error of 1.0 dB compared to 0.9 dB for CISM. The linear predictions were calculated by summing the sound levels for each receiver position in each octave band for PHASE. CISM used the standard approach of predicting the overall sound levels based on 500 Hz absorption coefficients and the measured overall sound power of the sound source with the appropriate directivity factors.

Overall it was seen that the predictions were accurate across the octave bands. However, for the 1 kHz octave band it was clear that PHASE was predicting a destructive interference effect at 2 m to 4 m when the measurements showed a constructive effect at the same distances from the sound source, resulting in an 8 dB difference in predicted sound levels. This was repeated for the 4 kHz octave band, but for distances in the range of 8 m to 30 m giving a predicted difference of up to 5 dB.

One possible explanation for the discrepancy in the predictions is that of the phase change on reflection. It has been assumed that there was no change on reflection, this appears not to be the case at these particular frequencies. In fact, the reverse seems to be true with destructive interference replacing constructive interference. Hence, an investigation could be performed where phase change on reflection was set to 180^0 and the sound propagation repredicted over the distance from the sound source of interest.

SUMMARY

The original PHASE model was refined to predict all the detail of the interference effects in a room, at the cost of execution time. In the very small reverberation room, a 1:2.5 physical scale model, both the low and high frequency ranges were accurately predicted in terms of shape and sound level. At the low frequency, 200 Hz, the interference effects were clearly predicted and at higher frequencies, 2 kHz and above, the modal effects cancelled each other, which agreed with the measurements. These results confirm Hodgson's assumption that wave effects were preventing the monotonic decrease in the sound level with increasing distance for the low frequency measurements.

The PHASE model demonstrated that pressure based modelling can be of practical use in industrial spaces both at predicting individual frequencies and the overall sound level, although, the advantages of predicting overall sound levels using pressure rather than intensity are limited and the costs high. However, the octave bands predictions did show interference effects, which were not modelled by the intensity based image-source model although it was seen that PHASE tended to predict destructive interference when constructive interference was actually occurring.

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