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ACCURACY OF THEORETICAL AND EMPIRICAL PREDICTIONS OF FACTORY SOUND FIELDS

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1. INTRODUCTION

In recent years, several methods for prediction of factory sound fields - particularly the sound propagation (SP) and reverberation time (RT) - have been developed. These include theoretical predictions by Lindqvist /1/ and Jovicic /2/, the latter work having been extended by this author /3/, empirical predictions by Friberg /4/ and acoustic scale modelling. It is the aim of this paper to consider the accuracy of these methods. First the two theoretical prediction methods are compared. Then Jovicic - based and Friberg predictions are compared with scale-model measurements in order to determine the prediction accuracy. Clearly such comparisons rely on the accuracy of factory scale-modelling techniques and, to some extent, on the accuracy with which it is possible to model a prototype factory. The latter accuracy is the subject of another paper at this conference /5/. The former accuracy is discussed in /3/ and will be mentioned here. Attempts at predicting factory, or model factory, sound fields reveal serious problems with the estimation of factory-acoustic parameters. This problem is also discussed.

2. PREDICTION METHODS

2.1 Theoretical prediction

The Lindqvist /1/ and Jovicic-based /3/ theories allow the prediction of SP and RT in factories with the following characteristics: rectangular shape; angularly-constant surface absorption coefficients which are uniform over any one surface; omnidirectional point source; variable source and receiver positions; empty or 'fitted' with isotropically-distributed, diffusely-scattering bodies of some density and absorption coefficient. Both theories employ a geometric acoustics/method of images approach. Unscattered and scattered energy contributions are considered separately and are determined from different impulse responses. Loss factors are introduced to account for surface, air and scatterer absorption. The RT can be determined from the rate of arrival of energy at a position from the image sources; the SP is determined from the total arriving energy.

The parameters in the theories are the factory dimensions, source and receiver coordinates, surface absorption coefficients, air absorption exponent, the average 'fitting' scattering cross-section volume density and the fitting absorption coefficient. Based on the case of spherical scatterers at high frequency, Jovicic calculated the fitting volume density as $Q = \Sigma S/4V$, in which ΣS is the total fitting surface area and V is the factory volume.

The Lindqvist and Jovicic-based theories differ with respect to the impulse response for scattered sound and the surface loss factors. There is evidence that the Lindqvist derivations are more rigorous.

2.2 Empirical prediction

Friberg /4/ developed empirical formulae for the prediction of the RT at 1kHz and the slope of the dBA SP curve from measurements in many factories. The parameters in his formulae are the factory height, the ceiling absorption at 1kHz and tabulated constants which depend on the factory shape and fitting volume density. As Friberg himself comments, the dBA SP curve varies with source spectrum; in practice it is similar to the SP curves for frequencies around 1kHz.

2.3 Acoustic scale modelling

A 1:50 scale factory model /3/ has been used extensively to investigate the acoustics of factory-like spaces and to obtain data for comparison with other prediction methods. The model, constructed of varnished plywood, has variable dimensions and source and receiver positions. Surface absorption and fittings can be introduced into the model. Air-jet noise sources are used as the continuous source of noise for SP measurements. Equalisation filters are introduced to flatten the spectral response of the source/receiver chain which, for SP determination, must be carefully calibrated for the effective source output power. The uncertainty associated with SP measurements in the 1:50 scale model has been estimated to be ±1dB, except at short source/receiver distances for which the uncertainty is higher. The uncertainty associated with RT measurements typically is ±10%. Accurate measurements are not possible above about 80kHz (1.6 kHzFS-FS=full scale) because of excessive air absorption.

3. PARAMETER ESTIMATION

A serious problem associated with factory scale modelling and with the prediction of factory or model factory sound fields is that of the accurate estimation of certain factory-acoustic parameters. Unfortunately, it is possible to predict correct SP or RT values with incorrect combinations of the parameters. Of course the factory dimensions, source/receiver positions and air absorption usually are known. However, experience has proven that it may be impossible to measure the relevant surface absorption properties, particularly of factory roofs /3/. This partly is because such properties may have to be measured in-situ, and partly because the sound field in a factory is non-diffuse. For both reasons, reverberation chamber measurements of surface absorption may be invalid. Also, it may be impossible accurately to determine the scattering properties of factory fittings. Even the simplified Jovicic method, described above, relies on accurate determination of the surface area of the fittings.

4. COMPARISONS MADE AND CONFIGURATIONS

Comparisons first were made between Lindqvist and Jovicic-based SP predictions. Then Jovicic-based, and Friberg, SP and RT predictions were compared with 1:50 model results. Comparisons were made for two very different shape configurations: a 'flat' configuration with dimensions 110 x 55 x 5.5 mFS^3, and a 'duct' configuration with dimensions 110 x 13.75 x 13.75 mFS^3. For SP, the source and receiver were at half height and width, with the source 5mFS from one end wall; predictions were made at appropriate source/receiver distances to 100mFS. For RT, a source/receiver distance of 20mFS was used. The theoretical predictions were compared for the case of 0.1 absorption coefficient and air absorption of

0.001 Np/m. The untreated varnished plywood model surfaces have a diffuse-field absorption coefficient of about 0.08 in the 1.25kHz FS test octave band for which model results are presented. The temperature and relative humidity, from which the air absorption can be calculated, were measured after each model measurement. Comparisons were made for the empty configurations and for the cases of the factories isotropically fitted with two densities of varnished timber cubes of side-length 2.25mFS. These densities corresponded to Jovicic Q values of 0.025mFS^{-1} and 0.05mFS^{-1}.

5. LINDQVIST VS JOVICIC-BASED PREDICTIONS

Figures 1a and b show the SP curves predicted by the Lindqvist and Jovicic-based theories for the duct factory when empty and fitted with $Q = 0.05\text{m}^{-1}$. As expected, the predictions are almost identical in the empty case. In the fitted case the Lindqvist theory consistently predicts lower levels at all but the shortest distances. The difference increases with distance and is 2.5dB at 100m. The differences were slightly less for $Q = 0.025\text{m}^{-1}$ and, for a given fitting density, were similar in the flat configuration.

6. THEORETICAL PREDICTION VS. 1:50 MODEL

In anticipation of the possibility that the diffuse-field absorption coefficient is not applicable in the cases considered, the following procedure was adopted for comparison of Jovicic-based predictions and scale model measurements: SP predictions were made for the empty factories using the known dimensions, source and receiver positions and air absorption, varying the surface absorption coefficient until a best-fit was obtained. Next, the known parameter values, the best-fit coefficient and the Jovicic Q-values were used to predict the fitted-factory SP curves. Finally, the above parameter values were used to predict the RT.

Figures 2a and b show the measured SP in the empty flat and duct model, and the predicted curves for the best-fit absorption coefficient value of 0.12; this is 50% greater than the diffuse-field value. Clearly the agreement between prediction and experiment is excellent-typically within 0.5dB - for both configurations. Figures 3a and b show the corresponding results for $Q = 0.05\ \text{mFS}^{-1}$. The results for $Q = 0.025\ \text{mFS}^{-1}$ were similar. In the flat case the Jovicic-based theory predicts too high levels at short distances, and too low levels at large distances. In the duct case the reverse occurs; predicted levels are high at short distances and too low at large distances. However, the disagreement is never greater than 3dB. It can be seen from Figures 1a and b that, in these cases, the Lindqvist theory would be expected to agree fairly well with experiment in the flat case at short distances and in the duct case at large distances. However, at large distances in the flat case, and at short distances in the duct case, the Lindqvist theory will be even less in agreement with experiment than is the Jovicic-based theory.

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TABLE 1

Comparison of theoretically predicted (Jovicic-based) and measured (1:50 scale model) RT's

Fitting density (Q in mFS^{-1})	Flat configuration		Duct configuration	
	Model	Theory	Model	Theory
0	4.25	4.3	4.05	4.1
0.025	2.8	2.1	3.7	2.4
0.05	2.15	1.75	2.3	2.05

Table 1 shows the corresponding RT results. The agreement between predicted and measured RT's is good for the empty model. However, in both fitted configuration the Jovicic-based prediction under-estimates the RT by as much as 50%. The theory correctly predicts that the RT decreases with increasing fitting density and is greater in the fitted duct case than in the fitted flat case. It has not yet been possible to make RT predictions with the Lindqvist theory.

7. EMPIRICAL PREDICTION VS. 1:50 MODEL

Comparisons were made between Friberg predictions, using 0.1 as the absorption coefficient, and 1:50 scale model results for the two shape configurations when empty and fitted. The 1.25kHz FS SP curves were taken to approximate the dBA curves; straight lines were fitted to these curves using linear regression and their slopes were calculated.

TABLE 2

Comparison of empirically predicted (Friberg) and measured (1:50 scale model) SP curve slopes (in dB/dd) and RT's

SHAPE	Q (in mFS^{-1})	SP curve slope		RT	
		Model	Friberg	Model	Friberg
FLAT	0 0.025 0.05	-2.2 -3.6 -5.2	-3.7 -4.0 -4.3	5.1 3.4 2.6	2.95 2.45 1.95
DUCT	0 0.025 0.05	-2.1 -4.4 -6.1	-2.75 -2.9 -3.05	4.9 3.5 2.7	4.5 4.1 3.7

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Table 2 shows the predicted and measured SP curve slopes (in dB per doubling of distance) and the 1kHzFS RT's. Considering first SP, it can be seen that Friberg's predictions overestimate the empty configuration slopes and, generally, underestimate the slopes in the fitted cases - particularly in the duct configuration. Despite the poor agreement with experiment, Friberg's method does predict that the slope increases with fitting density as was observed in the 1:50 model. However, contrary to observation, Friberg predicts the slope in the fitted flat configurations to be greater than in the fitted duct configurations. Considering now the RT, Table 2 shows that Friberg's prediction generally overestimates the RT. The RT is predicted to decrease with fitting density, as was observed in the mode. However, the RT is predicted to be considerably higher in the duct cases than in the flat cases, contrary to observation.

The main reason for the poor agreement between the Friberg predictions and experiment is that an important parameter determining the SP slope and the RT is the factory height. The factory volume is not a parameter; the volume only indirectly affects the various constants. The method predicts that the SP curve slope decreases, and the RT increases, with increasing factory height, approximately independent of the change of factory volume. Thus it predicts a lower SP slope and higher RT in the duct configurations than in the flat ones. That the measured result is contrary to prediction shows that the change of volume is also important.

8. CONCLUSIONS

Comparisons of predictions by the Lindqvist and Jovicic-based theories show that the two theories predict similar SP levels in empty factories. The Lindqvist theory predicts up to 3dB lower SP levels at source/receiver distances greater than about 10m in fitted cases.

A best-fit absorption coefficient of 0.12 has been found to give close agreement between Jovicic-based SP and RT prediction and empty 1:50 scale model measurements at 1.25kHzFS. Further, this coefficient and the Jovicic Q value for the fitting volume density give agreement within 3dB between prediction and the fitted 1:50 model results at the same frequency. It is likely that the Lindqvist theory has a similar accuracy. The results suggested that the Jovicic-based and Lindqvist theories and the Jovicic method for calculation of the fitting density are valid, at least at high frequencies and for cubic scatterers. The results also provide a further validation of the scale model techniques.

Poor agreement has been found between Friberg SP curve slope and RT predictions, and 1:50 scale model measurements. The results suggest that a main reason for this is that predictions do not account adequately for the influence of factory volume. Work is in progress to develop more comprehensive empirical factory sound field predictions /6/.

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5. R.J. ORLOWSKI 1984 Paper to be given at Acoustics '84, Swansea. Predicting factory sound fields using 1:50 scale models.

6. M. HODGSON 1983 Proceedings of Internoise '83, Edinburgh, 595-598. Empirical prediction of sound propagation and RT in factories.

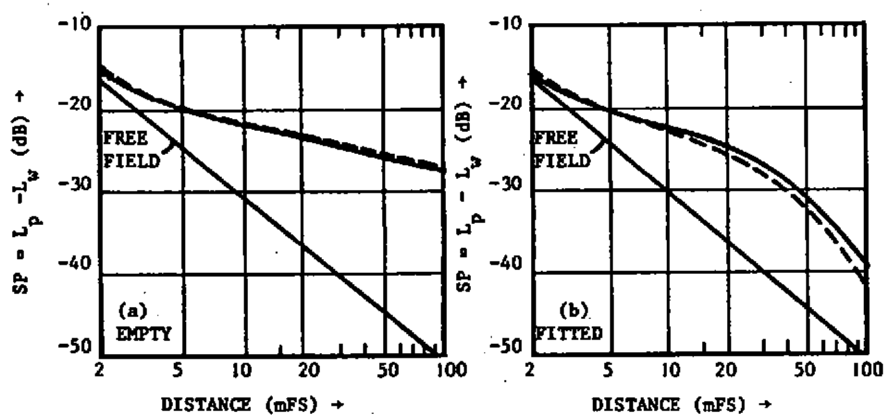

FIG. 1 Comparison of SP predicted by Lindqvist and Jovicic based theories in the empty and fitted duct configuration:—— Jovicic-based prediction; ---- Lindqvist prediction.

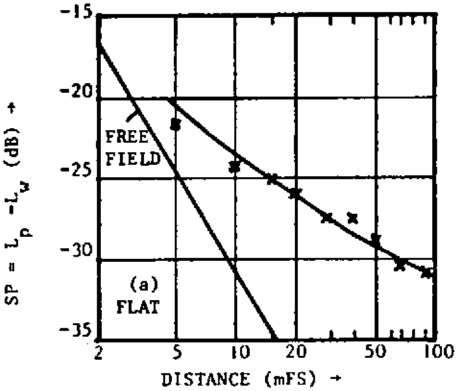

FIG. 2 Measured (1:50 model at 1.25kHzFS) and best-fit predicted (JOVICIC-based theory) SP in empty flat and duct configurations: X 1:50 model; —— prediction.

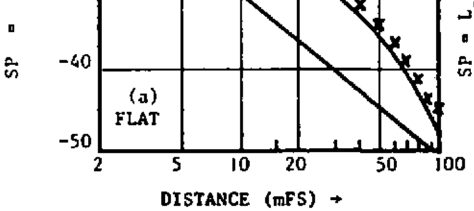

FIG. 3 Measured (1:50 model at 1.25kHzFS) and predicted (JOVICIC-based theory) SP in fitted flat and duct configurations with $Q = 0.05\ mFS^{-1}$: X 1:50 model; —— prediction.