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NOISE LEVELS IN FACTORIES: PREDICTION METHODS AND MEASUREMENT RESULTS

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1. INTRODUCTION

The introduction of more stringent legislation for limiting exposure to noise at the workplace has placed greater emphasis on gaining a better understanding of the behaviour and control of noise in factories. A specific objective is to develop an accurate method for predicting noise levels in factories so that the effect of various situations can be evaluated. There are four clearly defined cases where accurate noise prediction is required.

First, where noise levels are excessive and noise control must be implemented, it is necessary to compare the effectiveness of the various measures available. This is not only relevant to hearing conservation but also to the selection of the most economical solution.

Secondly, in new buildings, estimation of noise levels will permit noise reducing design features to be incorporated where necessary.

Thirdly, noise levels can be dependent simply on the layout of machinery which means that the layout can be optimised.

Finally accurate noise prediction in factories will enable future factory buildings to be designed to be inherently quieter.

The first part of this paper describes the characteristics of sound fields in factories and the factors which influence them. Then the various methods that have been proposed for predicting noise levels in factories are discussed. These fall into three groups, namely, empirical equations, physical scale modelling and theoretical predictions.

2. CHARACTERISTICS OF SOUND FIELDS IN FACTORIES

2.1 General Characteristics

A characteristic feature of the majority of factories is a shallow or flat shape which is due to the height being very much less than the length and often the width. This shape is markedly different from an average room so that the conventional theory of room acoustics does not apply.

In a room which has approximately equal dimensions and where the sound absorption is fairly uniformly distributed on all the surfaces, the sound level from a single continuous sound source will be uniform throughout the room except close to the source itself. This is a fundamental concept in Sabine's theory which assumes that the multiple reflections from the surfaces of a room result in a uniform distribution of sound energy; namely a diffuse sound field. This is illustrated in Figure 1.

In a flat enclosure the sound level from a single source never reaches a constant level but continues to decrease with increasing distance. This is similar to the behaviour of sound in open spaces although the decrease in sound level with distance is not usually as rapid.

In addition, the floors of factories are covered with obstacles which scatter and absorb sound and this also affects the rate of decrease of the sound level with distance. Figure 2 illustrates the behaviour of sound in flat enclosures with a typical curve giving the decrease of sound level with distance. This is referred to as a sound propagation curve and the term sound propagation has been defined as follows: Sound Propagation (SP) is the variation with distance from a point source of the sound pressure level (L_p) minus the sound power level (L_w).

$$SP(R) = L_p(R) - L_w, \text{ dB}$$

The term $L_p - L_w$ forms the ordinate of sound propagation graphs and means that the curves are independent of source power and therefore applicable to any source power.

In addition to considering sound propagation, it is also relevant to consider reverberation time (RT). Although RT is not directly related to steady state sound levels, it has a bearing on the annoyance experienced by workers to impulsive sounds. Figure 3 shows the RT in three typical factories which have roofs constructed of various types of lightweight cladding. The shape of these RT curves is characteristic of most factories of this construction; the maximum RT occurs around 1kHz with the shorter values at lower frequencies being due to the absorption and transmission of the cladding. Shorter values at higher frequencies are due to air absorption.

2.2 Factors influencing sound fields in factories.

Shape

As already mentioned, a majority of factories have a disproportionate shape which gives rise to a non-diffuse sound field. Some factories tend towards a flat shape whilst others have a duct shape; the effect of different shapes or aspect ratios is illustrated in Figure 4 for three fitted enclosures which have the same surface areas. The curves originate from computer predictions by Hodgson [1].

It can be seen that for a cube, the sound level 'levels off' after a short distance from the source and will remain relatively constant with distance. This is in agreement with Sabine's theory and is as expected.

On the other hand, for a flat shaped enclosure, the sound level decreases steadily with increasing distance from the source. The case is similar for a duct shaped enclosure except that the sound level decreases gradually at short distances and more rapidly at large distances.

Fittings

The fittings in a flat enclosure, whether they be machinery or equipment, will scatter incident sound energy and also absorb it to a certain extent. This will influence the sound propagation curves. The degree of scattering and absorption will depend on the size and density of the fittings and their absorption characteristics.

The example shown in Figure 5 is the plan and section of a factory together with sound propagation curves measured in it. Initially the factory was empty and it was then fitted with two different densities of machines. The change in the sound propagation curves is clearly evident both in terms of the overall drop in sound level and the change in the shape of the curves.

Surface absorption
Materials used for constructing the factory shell will have certain absorption coefficients and hence will influence the sound propagation. The most important element is usually the roof because of its large surface area. Often the roof will be constructed of lightweight materials such as profiled steel cladding which can cause considerable absorption at low frequencies resulting from vibration. This low frequency absorption will affect the low frequency sound propagation and reverberation time.

In summary, in flat or duct shaped factory enclosures the sound propagation and reverberation time depend on the following factors:

- enclosure shape
- absorption of enclosure surfaces
- density and size of machinery and fittings
- absorption of machinery and fittings

In order to be able to accurately predict the noise levels in a factory, accurate data on all these factors is required. The acquisition of some aspects of this data, for example the absorption of the enclosure surfaces, is complicated and is the subject of current research.

2.3 Evaluation of the overall sound pressure level
To evaluate the overall sound pressure level at any given location in the factory the following information is required:

(i) the sound propagation with distance curve in the fitted factory
(ii) the sound power of the machines.

From (i) we can determine the value of L_p-L_w, dB at any required distance R_1 from a machine and by adding the sound power level of the machine L_w, dB to this value we get the sound pressure level L_p, dB

i.e. $$L_p \text{ (at } R_1) = [(L_p - L_w) \text{ at } R_1] + L_w$$

$$= L_w \text{ (at } R_1)$$

Of course, factories contain many machines and this calculation must be repeated for each machine and all the sound energies must be added together to compute the final sound pressure level at the receiving point.

3. PREDICTION OF REVERBERATION TIME AND SOUND PROPAGATION IN FACTORIES

Three principal methods have been proposed for predicting reverberation times and sound propagation:

- Empirical methods
- Physical scale models
- Theoretical/computer models

3.1 Empirical methods
The best known empirical method is that proposed by Friberg [2] and is based on measurements in 139 factories in Sweden. The method is straightforward to use and permits

the evaluation of RT, sound propagation and the overall sound level reduction when absorption is applied to the factory ceiling. There are, however, several limitations, namely that the RT can only be evaluated at 1kHz and that the sound propagation curve is assumed to be a single constant slope whose absolute level is not defined. Despite these shortcomings Friberg's method remains attractive because of its simplicity.

In order to test the validity of the method, a comparison was made between predicted values and measured RT's in 15 fitted factories in the UK. The results are shown in Figure 6. It is evident that the predictions are in general accurate indicating that the method is valid for fitted factories.

A similar comparison made with empty factories showed that the Friberg method consistently underestimates the RT. Therefore it does not seem to be applicable to empty factories.

As RT curves in factories with roofs constructed of lightweight cladding have the characteristic shape shown in Figure 3, it should be possible to predict RT's in such factories at other frequencies besides 1kHz using Friberg's method. This could be done by incorporating a multiplication factor dependent on frequency into Friberg's RT equation, i.e.,

$$T = K_F\ (0.15h - 1.8\alpha + 1.8 + K_T)$$

K_F = frequency dependent multiplication factor
T = reverberation time in seconds (~ 1000Hz)
h = ceiling height in m
α = absorption coefficient of ceiling at 1000Hz
K_T = room constant according to Friberg [2]

From an analysis of measurements in the 15 fitted UK factories, a multiplication factor at 125Hz can be tenatively proposed as 0.63. Using this factor, a comparison has been made in Figure 7 of the measured and predicted values. The agreement is reasonable bearing in mind that the accuracy of measurements at 125Hz is less than at 1kHz. More measurements in fitted factories would enable this factor to be proposed with more confidence. The multiplication factor at 4kHz has been evaluated to be 0.75.

A comparison has also been made between predicted values of sound propagation and measured values in the 15 fitted UK factories. Because sound propagation plots are curved it has been proposed that they should be represented by two straight lines, one for source/receiver distances up to 20m, the other for distances greater than 20m [3]. In the present comparison, the predicted values have been compared with straight lines fitted to data in the source/receiver range 0-20m. The results are shown in Figure 8. It is evident that agreement between predicted and measured values is not impressive suggesting that Friberg's method for predicting sound propagation only gives a first order approximation.

3.2 Physical scale models

Physical scale models have the potential for recreating the full-scale sound field in miniature so that the effect of various configurations and noise control measures can be tested. In order to determine how accurately the sound field in a factory can be reproduced at model scale, a model of an existing factory was built at a scale factor of 1:16 [4]. Comparative measurements in the factory and its scale model showed good agreement: the reverberation times were generally within 10% and the values for sound propagation with distance generally within 2dB. The model was subsequently used to evaluate the potential of noise control measures, in particular suspended absorbers and barriers. The results of these experiments have provided some valuable data on the performance of these measures and in the case of barriers the model data compares well with published data relating to full-scale measurements. It may be concluded, therefore, that the use of a 1:16 scale model for predicting the potential of noise control measures in a factory is a viable technique. Moreover, it may be the only method applicable to complex practical situations which are not easily amenable to empirical and theoretical predictions. However, scale modelling is costly and the use of smaller models, at a scale of 1:50 say, does not appear to be feasible for factories [5]. Scale modelling, therefore, is likely to be of use as a research and development tool.

3.3 Theoretical/computer prediction models

There are two principal theoretical methods for predicting noise levels in factories, namely, the method of images as proposed by Jovicic [6] and subsequently adapted by others e.g. Hodgson [7] and Lindqvist [8], and ray tracing as proposed by Ondet and Barbry [9]. The two methods are related in that they both represent sound waves by rays but differ in the way reflected sound is generated. The method of images assumes reflected sound comes from image sources whilst in ray tracing rays are sent out from the source and are reflected at the room boundaries until they reach the receiver. Clearly both methods are computer based. The method of images is best suited to rectangularly shaped factories with uniform distributions of fittings. Ray tracing can cope with various geometries and uneven fitting distributions but is more demanding in computer power.

In order to determine the accuracy of these and similar prediction models, Hodgson [10] has compared predictions made using seven models with measurements in a full-scale factory. The results are shown in Figure 9. The general conclusion of his study is that the ray tracing method gives the best agreement with measurements. He also states that further investigations are required on how to estimate fitting density in factories to provide accurate input data for models.

4. CONCLUSIONS

Work in the last few years has led to a greater understanding of the behaviour of sound in factories and there is currently a strong interest in producing an accurate prediction method. Of the various prediction methods available physical scale modelling will probably serve as a research tool and empirical formulae will be used to give first order approximations. Computer based prediction models are constantly improving although further work is required on accurately determining the absorption characteristics of construction materials and means of quantifying the effect of fittings. This work is currently in progress.

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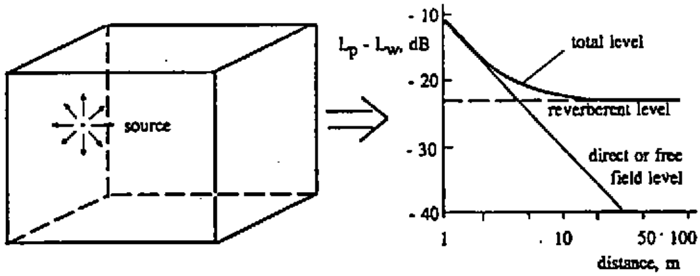

Figure 1. A proportionately shaped room exhibits a constant sound level except close to the source.

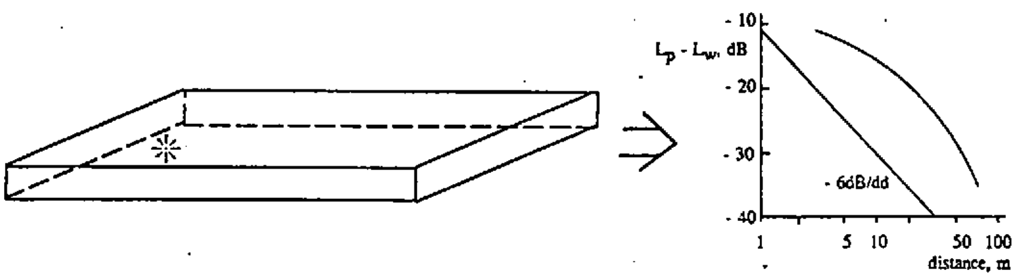

Figure 2. In a flat shaped room the sound level decreases with increasing distance from the source.

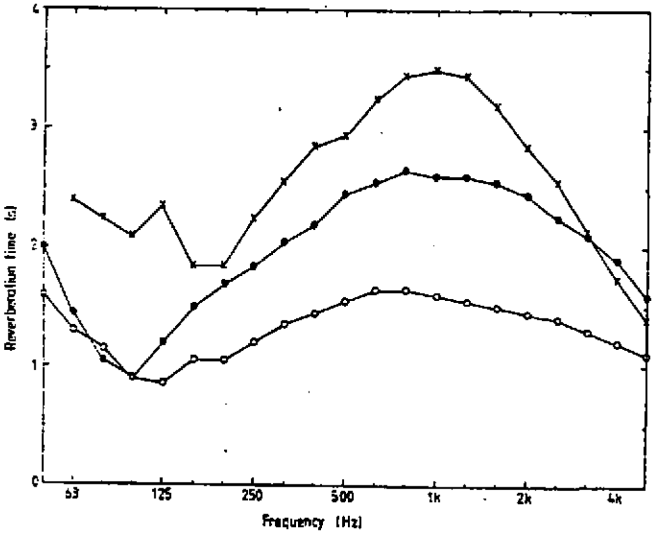

Figure 3. Measured reverberation times in three fitted factories with roofs constructed of cladding

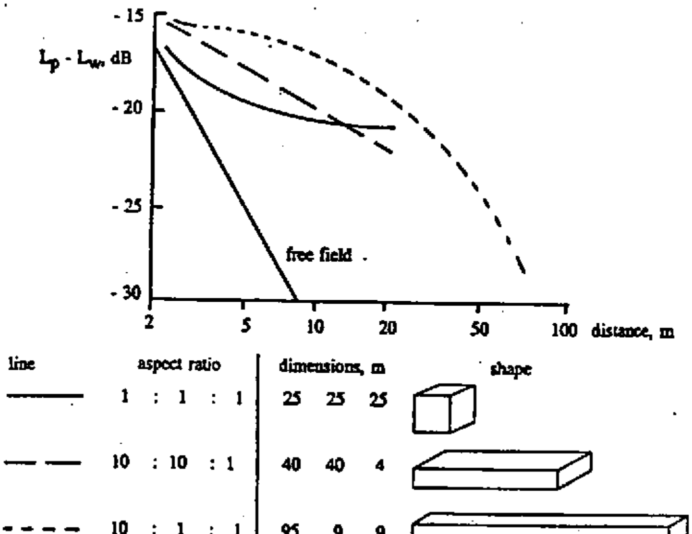

Figure 4. Predicted sound propagation curves in three fitted enclosures with different shapes but the same surface area (after Hodgson)

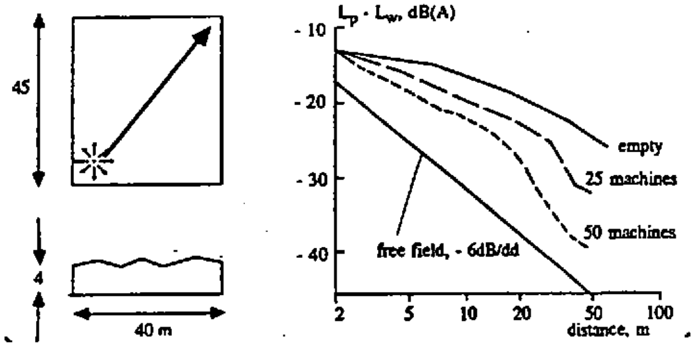

Figure 5. Measured sound propagation curves in a factory when empty and fitted with different numbers of machines.

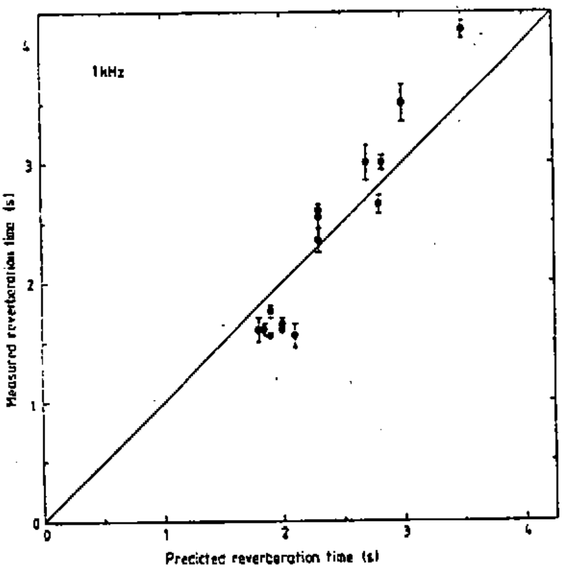

Figure 6. Reverberation times predicted by Friberg's method compared with measurements.

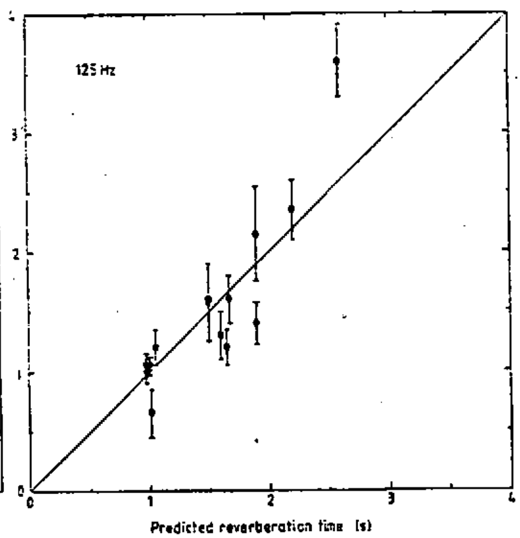

Figure 7. Reverberation times predicted at 125Hz by modified Friberg method compared with measurements.

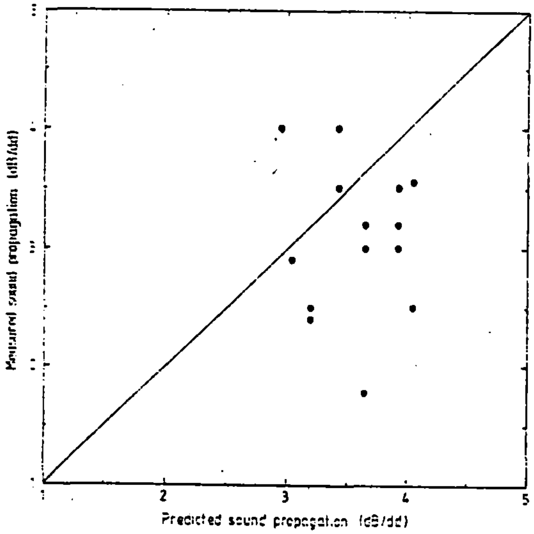

Figure 8. Sound propagation predicted by Friberg's method compared with measurements.

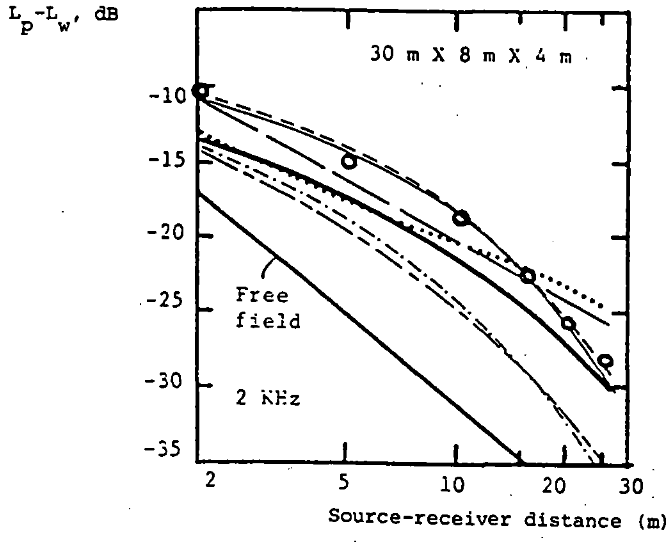

Figure 9. Measured sound propagation in a fitted factory (0) compared with predictions according to the following models: ——— Friberg; —·—·— Jovicic; ·········· Lemire; ------ Hodgson; — — — Kurze; ——— Lindqvist; ——— ray tracing. (after Hodgson).