FACTORY SOUND FIELDS - THEIR CHARACTERISTICS AND PREDICTION

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ABSTRACT

This paper presents the main results of completed and on-going research, mainly by the author and his colleagues, into factory sound fields. The important factors influencing the sound propagation and the reverberation time in factories are discussed. In particular, the obstacle effect resulting from the presence of fittings, and the influences of enclosure shape and construction, are elucidated. Methods for predicting factory sound fields are reviewed and evaluated.

SOMMAIRE

Cet article présente les résultats principaux de la recherche effectuée, surtout par cet auteur et ses collègues, sur les champs sonores en locaux industriels. Les importants facteurs qui influencent la propagation du son et le temps de rérverbération sont discutés. En particulier, l'effet d'obstacle qui résulte de la présence du contenu du local, et les influences de la forme et de la construction du local sont élucidés. Des méthodes pour la prévision des champs sonores sont revues et évaluées.

1. INTRODUCTION

The last decades have seen an increase of interest in, and need for, a better understanding of noise in factories and for accurate factory-noise prediction methods. This increase was stimulated by a greater awareness of the adverse effects of noise on man, and by increasingly stringent recommendations and regulations governing the noise exposure of factory workers. These were aimed at limiting hearing hazard resulting from worker-related aspect of factory noise; another factor, not dealt with in existing regulations, is that of the subjective satisfaction with the acoustic environment.

Noise in factories results from noisy machinery, processes and operations. Noise levels are enhanced by the confinement of the sound energy in the factory enclosure, resulting in the noise-exposure levels to which workers are subjected. In the case of impulsive noises, the enclosure also results in reverberance, caused by the finite rate of sound decay. Reverberance is believed to be related to the perceived worker satisfaction with the working environment, though this has yet to be proven or quantified. It is a common experience of the acoustic consultant that factory noise-reduction measures, even when little affecting noise-exposure levels, considerably improve the working environment by reducing reverberance.

An understanding of, and an ability accurately to predict, the sound field in a factory are essential for the estimation of probable worker noise exposure and satisfaction. They also allow the possibility of planning; that is, design of the factory enclosure, as well as noise source and worker-location layouts, in order to minimise noise exposure and annoyance. Further, in the case of existing factories, they permit evaluation of the efficacy and cost-effectiveness of enclosure noise-reduction measures.

Discussions with practitioners reveal that all too often, when they estimate noise levels or the efficacy of possible noise-reduction measures, the well-established Sabine theory, developed for auditoria, is applied. Unfortunately, for many factory spaces their application is invalid, as will be shown.

This paper presents some results of on-going research into factory sound fields, with emphasis on work carried out by the author and his collegues. This research has three main objectives:

1. To gain an understanding of the main factors influencing, and the characteristics of, factory sound fields;
2. To apply this knowledge to improve the factory acoustic environment;
3. To consolidate and evaluate methods for predicting factory sound fields.

A study of factory sound fields is a study of sound fields in enclosures with non-diffuse sound fields. However, factories are only one example of enclosures which have substantially non-diffuse sound fields. Thus the research results have relevance to other such enclosures - for example, corridors, open-plan offices and concert halls.

2. SOUND FIELD MEASURES

The sound field in a factory may usefully be characterised by two measures, one describing the steady-state spatial, and one the temporal, behaviour of the field. These are, respectively, the sound propagation (SP) and the reverberation time (RT). The SP is the variation of the sound pressure level (L_p) with distance, R, from an omnidirectional point source located at a position in the factory. SP is measured in octave bands or dB(A). The L_p can be normalised to the output sound power level (L_W) of the source; that is, SP(R) = L_p(R) - L_W in dB. SP prediction is of the utmost importance, being required for the prediction of the total noise level at a receiver position in the factory; the total level is the energy sum of the level contributions from the individual sources at the position, as given by the SP(R) and the source L_W's.

The RT is the usual room-acoustic measure, related to the rate of sound decay in the enclosure. It is normally measured in full or third-octave bands and is determined from the average of values measured at a number of source and receiver positions. The relevance of RT to factories is less obvious than is that of SP, and is a matter of some discussion among acousticians and consultants. As was mentioned above, it is likely that RT is related to the annoyance caused by impulsive sounds.

It is important to consider which frequencies are of interest in factories. Noise in factories may occur at all audio frequencies. However, the important measure for the prediction of noise-exposure levels is the A-weighted L_{eq}. Because of this weighting, low and high frequency factory noise usually, though by no means always, is of little importance. In this research frequencies corresponding to octave bands from 125Hz to 4kHz were investigated.

3. FACTORIES VS 'SABINE' SPACES

The theory of Sabine describes the spatial and temporal behaviour of sound in enclosures which are empty, which have all three dimensions similar, and in which the surface absorption is uniformly distributed. In such enclosures the pattern of sound reflection from the enclosure surfaces is such that at any position equal amounts of sound energy propagate in all directions - the sound field is diffuse. The theory predicts a steady-state sound field composed of two contributions, as shown in Figure 1 for the cases of low and high total absorption. Within a certain distance from a sound source (the so-called "reverberation radius") a "direct field" dominates. This is unaffected by the enclosure and has a level which decreases at a rate of -6dB per doubling of distance, due to spherical divergence. At larger distances, sound reflected from the enclosure dominates, resulting in a "reverberant field". Its level tends to decrease with volume and decreases with total absorption, but does not vary with source/receiver distance.

Regarding the temporal behaviour of the sound energy during sound decay, the level decays exponentially. The rate of decay is directly proportional to the factory volume to surface area ratio, and is inversely proportional to the total sound absorption, this being composed of surface absorption, as characterised by the diffuse-field absorption coefficient, and of air absorption.

Factories usually have mutually similar construction. The enclosure is erected over a floor of concrete and is supported by a portal frame system. The walls usually consist of glazing, masonry and/or cladding. The roof, sometimes singly or multiply pitched, or sawtooth, consists of insulated metal, asbestos and/or plasterboard panels which are mounted on purlins attached to the portal frames. Some factories have a flat, suspended inner ceiling. Of course factories may contain many fittings -machines, stock, workshops, services - distributed throughout the space and over its surfaces, especially the floor. Factory spaces differ from those described by the Sabine theory with respect to their contents, shape and surface absorption. Because of these differences the assumptions of the Sabine theory are not met. The factory sound field may be highly non-diffuse, the SP and RT characteristics of factories may not be a described above. Predictions using the classical theories may be highly inaccurate. This will be discussed in more detail below.

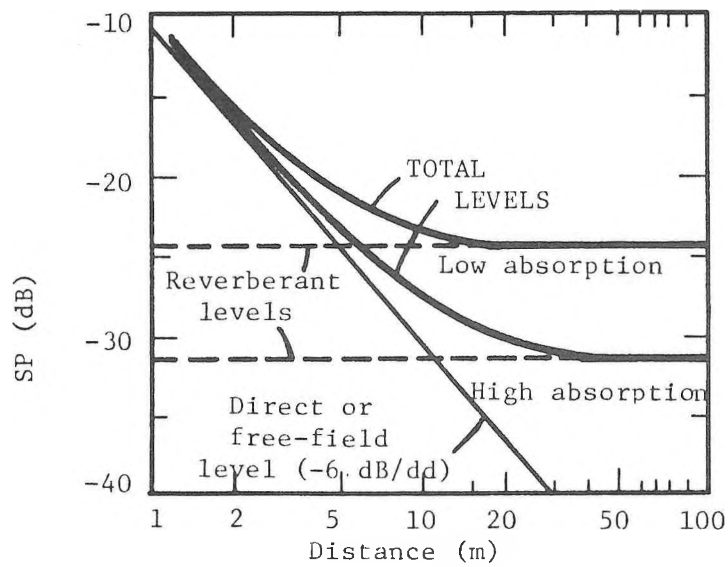


Figure 1. Direct, reverberant and total field SP's predicted by the Sabine theory for a large enclosure with low and high total absorption.

4. CHARACTERISTICS AND INFLUENCING FACTORS

In order to carry out the first of the above research objectives, theory based on the method of images approach (discussed below) was employed. RT and SP measurements were made in 45 factories of various sizes, shapes and constructions, when either or both nominally empty or fitted. A variable 1:50 scale factory-like model was used as a research tool. This consisted of a timber box with variable dimensions; absorbent materials and scattering objects could be introduced to model surface absorption and fittings. Full details of this work are published elsewhere [1,2,3].

What then are the main factors influencing factory SP and RT?

4.1 Fittings

A particularly important attribute of noisy factories is that they are fitted. Figure 2 shows the dB(A) SP measured along a diagonal of a factory when it was empty, partially fitted with 25 machines and fully fitted with 50 machines. Figure 3 shows the corresponding measured RT curves. The factory had average dimensions of $45m \times 40m \times 4m$, was of asbestos cladding construction and had a triply-pitched roof. The machines were metal-sheeting machines with typical dimensions of $2m \times 2m \times 1m$. Clearly the introduction of fittings decreased levels, especially at larger source distances, and the RT at all frequencies. The decreases were roughly proportional to the number of machines.

In a fitted factory - in fact, even in an unbounded region containing scatterers, sound propagates from the source to the receiver by an infinite number of paths as it "bounces between the fittings (and the walls, if present). Sound energy radiated from the source at a certain time arrives at the receiver continuously over a long period of time; there is reverberation even if there are no bounding surfaces. Further, the sound may strike the surfaces and arrive at the receiver from any direction. The presence of fittings in a factory causes a redistribution of sound energy, relative to the case of no fittings, towards the source due to backscattering. The fittings also increase the propagation losses in two ways. First, sound may be absorbed by the fittings. Secondly, and more importantly, the presence of fittings causes more sound to be scattered onto the bounding surfaces, effectively increasing their absorption. This 'apparent' absorption can be considerable - in fact many times greater than the fitting surface absorption. Further, the apparent absorption tends to be highest at frequencies at which the empty factory surface absorption is highest [4]. The effect of fitting scattering increases with the fitting volume density. Scale model studies have shown

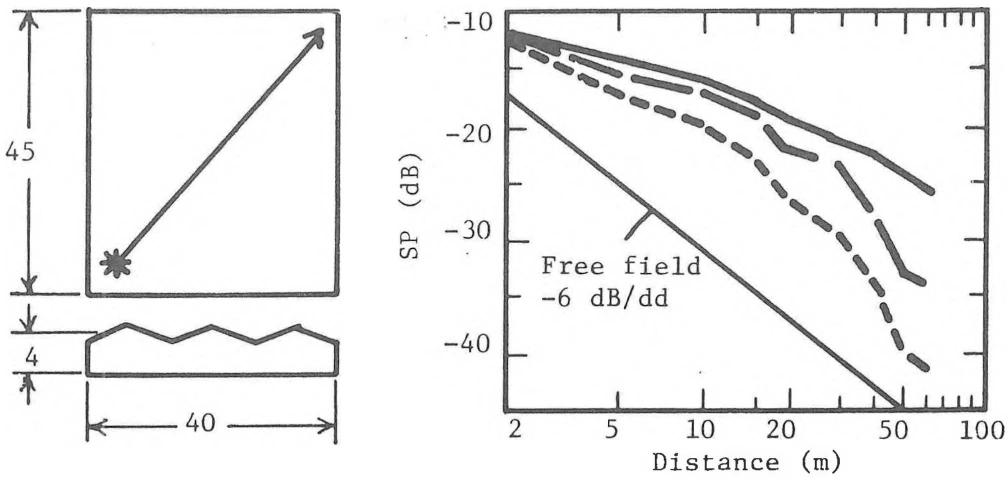


Figure 2. Measured dB(A) SP in the factory shown at left when empty (———) and fitted with 25 (— —) and 50 (- - - -) machines.

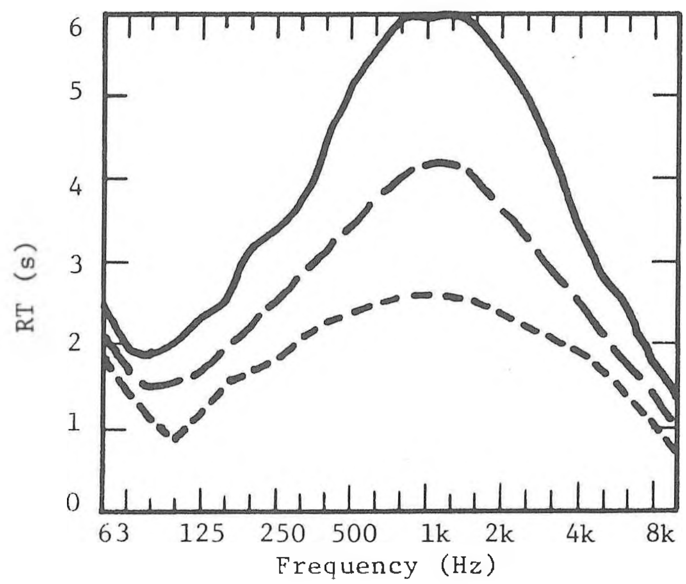


Figure 3. Measured third-octave band RT in factory shown in Fig. 2 when empty (———) and fitted with 25 (— —) or 50 (- - - -) machines.

that the SP and RT are approximately independent of the vertical distribution of the fittings 3; however if there is a large roof void sound may propagate in this 'empty' region, partially by-passing the fittings [5]. Further model experiments, using timber blocks of two different sizes as the fittings, suggest that fitting scattering depends on the fitting surface area. This is supported by full-scale measurements of the influence of fittings carried out by the INRS of France. They also showed that fitting orientation can be important [5]. Finally, as will be further discussed below, there is evidence that significant surface scattering occurs even in nominally-empty enclosures, presumably due to surface contouring.

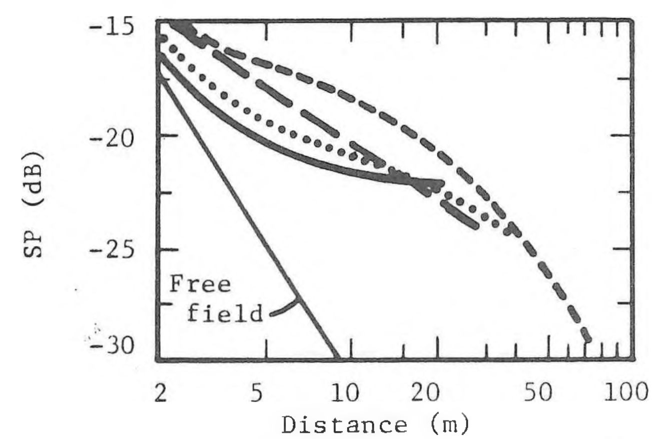
4.2 Enclosure shape – aspect ratio and volume

Clearly, factories have different shapes and sizes. They are usually large and disproportionate, with height much less than length and, often, width. Further, factories may have non-flat roofs; pitched or sawtooth roofs are not uncommon. More extremely, factories may be L- or T-shaped or have partial partitions which form coupled spaces. Here discussion is restricted to factories which are rectangular in plan shape and which have no partial partitions. Consideration of the surface reflection pattern shows that disproportionate shape or a non-flat roof results, at all positions, in a non-uniform angular distribution of the incident sound - that is, in a non-diffuse sound field.

The aspect ratio of the factory enclosure can significantly affect its SP characteristics. This is demonstrated in Figure 4 which shows the predicted SP curves for four moderately-densely-fitted enclosures of different shapes, but with the same surface areas. All have the same uniformly-distributed surface absorption and no air absorption; thus, the empty factories would all have the same Sabine reverberant-field level ($SP_{rev,empty} \simeq -20.5dB$). Clearly the SP curve shape varies considerably with aspect ratio. Only in the case of the cubic enclosure does a uniform reverberant level even approximately exist. In all other cases levels decrease monotonically with source/receiver distance. In general short-distance levels increase, and large-distance levels decrease, with increasing disproportionality.

The influence of aspect ratio on RT is complicated [1]. In truly empty, disproportionate enclosures the sound decay is expected to be non-exponential and the RT is difficult to determine; in any case the rate of decay varies with shape. In fitted factories the sound decay is expected to be substantially exponential and the RT decreases with aspect ratio. In practice sound decays measured even in highly disproportionate, nominally-empty factories tend to be more or less exponential. This must again be due to ambient surface scattering, and may imply that the effect of aspect ratio is less than expected.

The influence of volume changes on RT and SP are also complex [1]. Generally the RT increases with the enclosure volume to surface area ratio as predicted by the Sabine theory. Further, SP levels tend to decrease with increased volume. However the magnitudes of the changes which occur depend on the magnitude of the volume change and, in the case of SP, on which dimension is changed.



LINE	L : W : H	L	W	H
	1 : 1 : 1	25	25	25
	5 :2.5: 1	48.4	24	10
	10 : 10: 1	40	40	9
	10 : 1 : 1	95	9	9

Figure 4. Predicted SP in four fitted enclosures (details in table; dimensions in metres) with the same surface areas but different aspect ratios.

4.3 Enclosure shape - roof contour

In empty or uniformly fitted factories with flat roofs; the SP does not vary significantly with direction. However, roof contour results in directional SP variations, as illustrated in Figure 5. This figure shows the

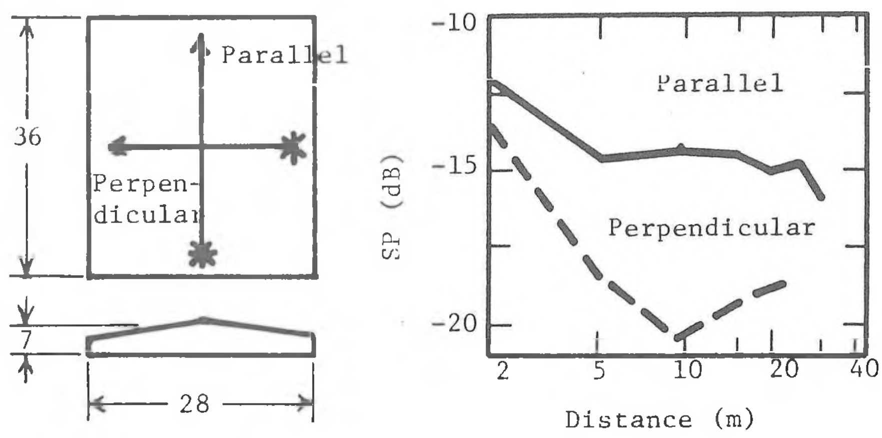


Figure 5. Measured 250Hz SP in two perpendicular directions in a factory with a singly-pitched roof.

250Hz SP measured along the two major axes in a factory with a singly-pitched roof as shown at left. Levels in the two directions differed by up to 6dB, and were lowest in the perpendicular direction. The differences were greatest at low frequency, decreased with frequency and were negligible above 500Hz. Similar measurements were made in a scale model with a flat, single-pitched or a triply-pitched roof [3]. In general levels were higher than flat-roof levels in directions parallel to the roof contours, and were lower in perpendicular directions. The effect was greatest with a singly-pitched roof, and decreased with roof height and fittings. The effects did not vary much with frequency. That this was contrary to the case of full-size factories suggests that the effects are not simply due to enclosure geometry, and require further study.

4.4 Surface absorption

Surface absorption strongly affects factory sound fields. All factory enclosures have a certain amount of ambient surface absorption which depends on the factory construction. The absorption of concrete and brick or blockwork is small, and increases with frequency. On the other hand panel roofs, suspended ceilings and glazing, for example, may have considerable effective absorption at low or middle frequencies owing to their acoustically-induced, vibration-response characteristics [6]. Since the RT is inversely related to the total (surface plus air) absorption in an enclosure, much can be learned about the ambient absorption by looking at the shapes and magnitudes of measured factory RT spectra - see, for example, Figure 3. In fact, similar information is provided by the frequency variation of the large-distance SP levels. Figure 6 shows the estimated absorption coefficient of two common roof constructions, as estimated from measured empty-factory RTs. The constructions are:

TYPE A - Double panel construction. The outer panel is of corrugated asbestos; the inner panel is of flat asbestos or plaster-board. The panels may be separated by battens and the resulting space may contain insulation. This construction is typical of older British factories;

TYPE B - Steel-deck, consisting of an interior corrugated-steel panel with insulation, asphault and gravel above. This construction is typical of North American factories and of some new British factories.

It should be mentioned that there is evidence that the effective absorption of some newer, light-weight constructions, consisting of a metal/solid-foam sandwich, occurs at the more subjectively-important mid-frequencies. There is also evidence that in certain cases the angular variation of the effective absorption of factory roofs may significantly influence the sound field [7].

4.5 Characteristics

Figure 2 well demonstrates the general characteristics of empty and fitted factory SP curves. All three curves

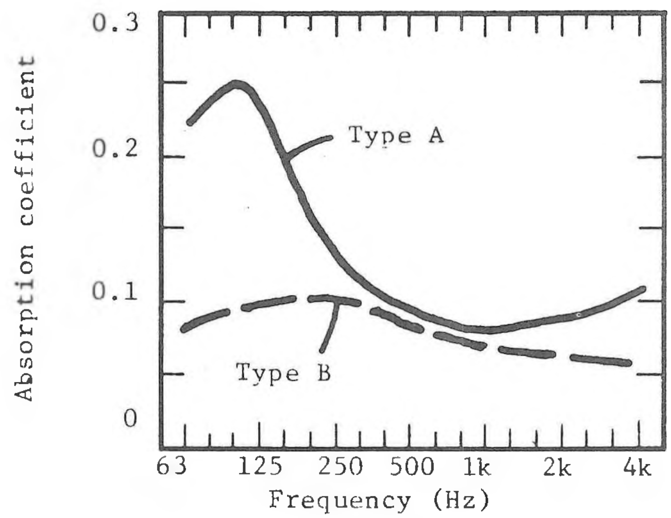


Figure 6. Estimated effective absorption coefficient of two common factory roof constructions: Type A - double asbestos panel; Type B - steel deck.

approach the free-field SP curve at short distances. However, levels at 1 or 2m from the source may be several decibels above free-field levels at all frequencies. That is, the enclosure and fittings can significantly influence operator positions, contrary to common belief. In empty factories the SP curve slope remains approximately constant, or decreases with frequency; in fitted factories the slope tends to increase with distance. In the case of dense fitting the SP curve may cross the free-field line at large distances.

5. CONTROL OF FACTORY NOISE

The aim of factory noise control is to improve the work environment by the reduction of noise-exposure levels and of reverberation. This may be done either at the design stage, or after the factory is built. As mentioned, the important quantity for the prediction of noise-exposure levels in a factory containing many noise sources is the sound pressure level at positions throughout the factory. The L_p at position R is the energy sum of the level contributions from each source at R, as determined from SP(R).

Clearly, the more specific objective of noise control is to minimise the RT, and the SP in the appropriate source/receiver distance range. At the design stage the factory shape and construction can be optimised. After construction, the RT can be reduced by increasing the total propagation losses. SP levels at short and large distances are reduced by increasing propagation losses and by reducing and increasing respectively, the redistribution of sound energy due to fittings. Table 1 shows some factory-acoustic parameters which can be modified in order to reduce the SP and RT in fitted factories, and the changes required.

Several further comments are necessary in relation to these results. First the distance which delimits the short and large-distance region is typically 10 – 20m. Also, the short-distance region can extend to as close as 1 – 2m from a point source and, therefore, may include operator positions. Secondly, it is clear from Table 1 that the changes of some parameters, required to reduce the SP and the RT, are often in conflict. The same is true with respect to simultaneous reduction of short and large-distance SP levels. If, for example, it is required to reduce all variables, then the only feasible measure is to increase the surface and fitting absorptions. Measures only causing an energy redistribution are inapplicable. Thirdly, it should be noted that, in many factories, it is not possible to modify the floor, side and end-wall absorption.

Because the presence of scatterers increases the effective surface absorption, a combination of scatterers and surface absorption may be especially effective for the reduction of large-distance levels and of the RT. More

TABLE 1

Changes of factory-acoustic parameters which reduce the SP and RT in empty and fitted factories (↑ increase, ↓ decrease)

Parameter	SP (short)	SP (large)	RT
Width:height ratio	↑	↓	↑
Height	↑	↓	↓
Surface absorption and distribution	↑ on surfaces nearest the source	↑	↑
Fitting density	↓	↑	↑
Fitting absorption	↑	↑	↑

generally, since the factory ceiling is often a low-frequency absorber, low-frequency scatterers, which are mid and/or high frequency absorbers, may be a particularly cost-effective treatment. A further reduction of large-distance levels may be achieved if scatterers are located in the roof void, blocking the propagation path which may short-circuit the lower fitted region. A possible application of these principles is the use of solid acoustic baffles, hanging at random locations throughout the roof void. A second possibility is the use of scatterer/absorbers of inverted pyramidial shape, suspended above individual noise sources. The scatterers should have dimensions of at least 2m to provide adequate low-frequency scattering. Their surfaces should be covered with porous absorbent to provide mid and high-frequency absorption.

One important observation, relevant to factory design, must be made about factory height. It normally is expected that decreasing the height increases noise-exposure levels by increasing the sound energy density; this is the case in empty factories. However, as discussed above, decreasing the height of fitted factories also increases the fitting volume density and causes a redistribution of sound energy, tending to decrease large-distance SP levels. In some cases this may result in decreased noise-exposure levels, contrary to expectation. An example of this is discussed in [7]. Of course, decreasing the height also reduces the RT.

Finally, a non-flat roof can, in principle, be used to reduce large-distance SP levels in certain directions. Source and receiver locations should be laid out so as to maximise source/receiver distances and the beneficial effects of non-flat roofs.

6. PREDICTION OF FACTORY SP AND RT

What tools are available for the prediction of factory SP? It has been established that the Sabine theory is not generally applicable. There are three main practicable alternatives: physical scale models, empirical formulae and geometric-acoustic models.

6.1 Physical scale modelling

Scale modelling has the obvious advantage that, in principle, any factory configuration can be modelled. The feasibility of factory scale modelling has been demonstrated by successfully modelling an existing factory at 1:16 scale [8]. The factory, which produced light-bulbs, had average dimensions of $120m \times 45m \times 9m$ and was of typical construction with a singly-pitched roof of asbestos-panel cladding. The walls and floor of the model were constructed of varnished timber and plastic. The roof construction was based on a distributed Helmholtz-resonator principle. The fittings were timber and cardboard blocks and tin cans of the approximate sizes and shapes of the main factory fittings. Figure 7 shows the RT measured in the full-size and scale-model factories. The agreement is generally within 10%. Figure 8 shows the corresponding dB(A) SP results. The accuracy of modelling averaged 0.5dB(A): that in the individual octave bands averaged 1.5dB. This 1:16 scale model has also been used to investigate the performance of two conventional noise-reduction techniques - functional absorbers and barriers [8].

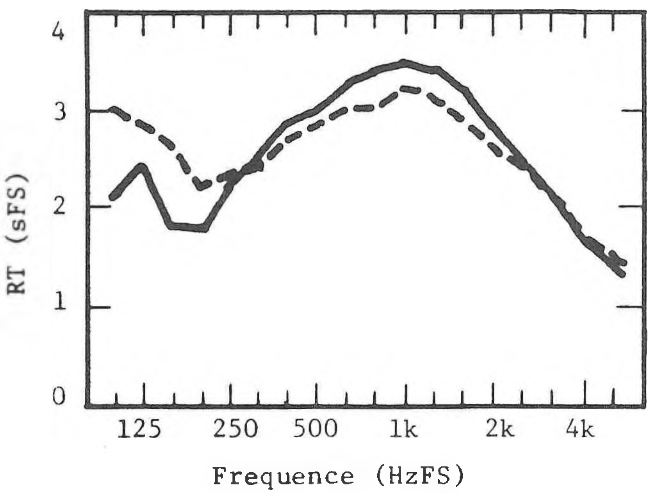


Figure 7. Measured third-octave band RT in a full-size factory (——) and in its 1:16 scale model (- - -).

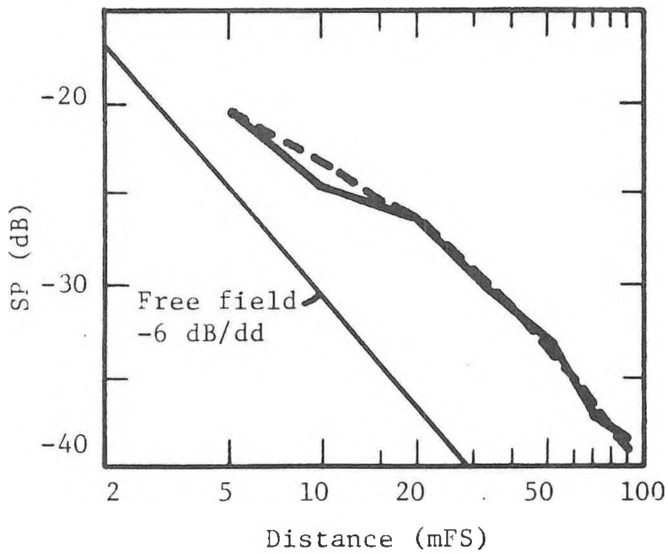


Figure 8. As Fig. 7 but for the measured dB(A) SP.

Clearly, if scale models are to be used as design aids, which must be cost-effective, small scales must be chosen. Unfortunately, research aimed at evaluating factory scale modelling at 1:50 scale [2,3] has shown the accuracy to be unacceptably low for several reasons. First, scale models have an upper limit for accurate scaling of air absorption. For 1dB accuracy this is about 2.5kHzFS (FS = full scale) at 1:16 scale, but only 800HzFS at 1:50 scale. An 800HzFS limit makes the accurate determination of dB(A) levels impossible. Secondly, the non-omnidirectional response of even the smallest available microphones at the high model test frequencies significantly influences the SP measured in disproportionate, non-diffuse-field factory models. Thirdly, the absorption coefficient of varnished timber, the most convenient material for modelling acoustically-hard factory surfaces, is in some cases too absorbent.

6.2 Empirical formulae

Empirical formulae derived from factory measurements, such as those developed by Friberg [9], have the advantages of ease and speed of use. Their disadvantages are, of course, reduced accuracy and lack of sensitivity to parameter changes. The Friberg formulae are inaccurate in assuming the SP curve to be of single, constant slope (see Figure 2). Further, they disregard the absolute level of the SP curve and provide limited frequency information. Work is in process to develop more comprehensive empirical formulae [10].

6.3 Geometric-acoustics theory

Geometric-acoustics models are based on a high-frequency approximation and may not be accurate at low frequencies. Ray-tracing methods have been applied to factories with some success [11]. They have the advantage of being able to deal with irregular factory configurations, and to include individual barriers and surface scattering.

An alternative approach is that of the method of images. Its application to empty, parallelepipedic enclosures is well known [12,13]. Borish [14] has extended the method to arbitrary polyhedra. L'Espérance et al. [15] have incorporated barriers into an SP prediction. Jovicic [16] and Lindqvist [17] among others, have extended the image method to the prediction of SP in enclosures containing isotropically-distributed fittings. The Jovicic theory has been extended by this author [1]. According to these theories the fittings are quantified by their average scattering cross-section density, Q in m^{-1}. Lemire and Nicolas [18] suggested a simpler way to account for fittings - the image energy is exponentially attenuated as the sound propagates through fitted regions.

Efforts have been made to evaluate the applicability of the extended Jovicic theory as a prediction tool. This has been accomplished by comparing predictions with the results of measurements made in the variable scale model and in full-size factories [19]. It is clear that the theory qualitatively describes many observed factory-acoustic characteristics, such as the influences of enclosure shape, surface absorption and fittings. However, its accuracy is limited by not incorporating the influence of roof contour or non-uniform horizontal-plane fitting distributions.

Quantitative evaluation has proved more difficult. A problem common to the use of any prediction theory (and often not sufficiently considered) is that of the accurate determination of the parameter values. In the case of factories what, for example, is the effective absorption of a given factory cladding? What is the scattering cross-section density of a given factory's fittings? In principle, the parameter values for the simplified factory scale model are readily established. In practice this has not always been found to be the case. For example, in certain cases the changes of SP and RT which occurred in the model when porous surface absorption was introduced in no way correlated with the measured diffuse-field absorption of the material [3].

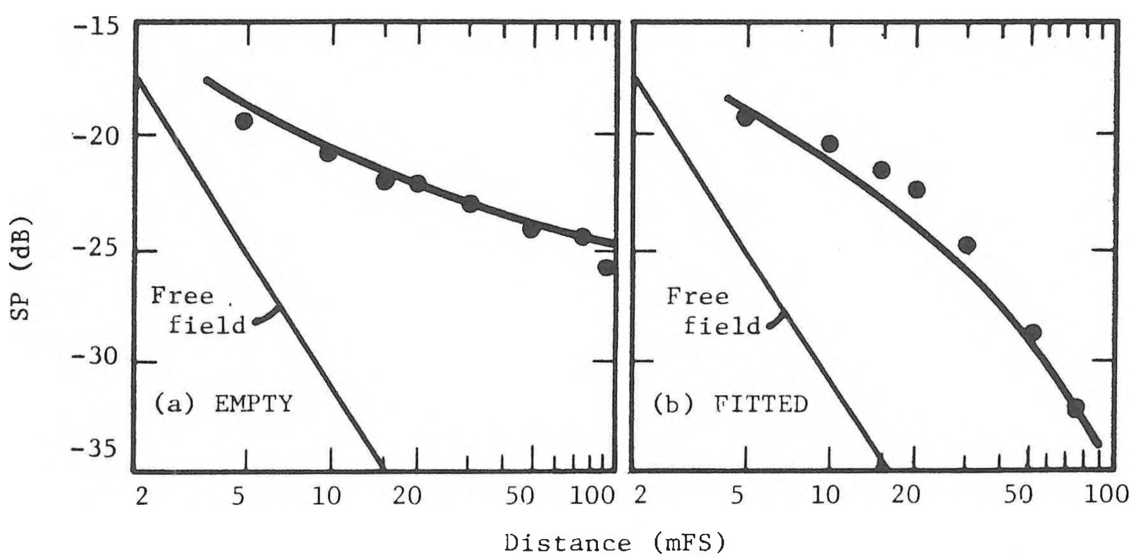


Figure 9. Measured (● ●) and predicted (———) 315HzFS SP in a 1:50 scale model when empty and fitted.

In any case, Figure 9 shows the 315HzFS SP measured in the variable 1:50 scale model with dimensions 110mFS$\times$55mFS and 5.5mFS and varnished plywood surfaces, when empty, and when fitted with 220 varnished timber cubes with 2.2mFS side length (Jovicic scattering cross-section density, Q $= 0.05m$FS^{-1}).

Also shown are the curves predicted by the extended Jovicic theory using the relevant air absorption exponent ($m = 0.0005Np/m$), the measured diffuse-field absorption coefficient of varnished timber ($\alpha = 0.065$), and $Q = 0.05mFS^{-1}$. Clearly the agreement is excellent, within 1.5dB, in both cases and at all source/receiver distances. In other frequency bands and shape configurations the agreement was equally good. In general the results suggest that the theory fairly accurately models the influence of shape, surface absorption and fittings - at least in the case of a simple scale model.

Comparisons have also been made between predicted and measured SP's for 30 empty factories [20]. This was first done using Q = 0 and the known prediction parameter (e.g. dimensions, air absorption) values, but varying the value of the unknown parameter (the surface-absorption coefficient) to see if a satisfactory best-fit could be obtained. This has led to several conclusions:

a) Most nominally-empty factories show SP characteristics associated with fitted factories. As mentioned above, this is presumably due to ambient surface scattering.

b) In most cases predictions made using the absorption coefficient obtained from the measured RT using the Eyring theory gave agreement with measurement within 1dB at source/receiver distances less than about 20m, but overestimated the SP at larger distances.

c) In most cases agreement within 1dB could be obtained using an appropriate non-zero Q value.

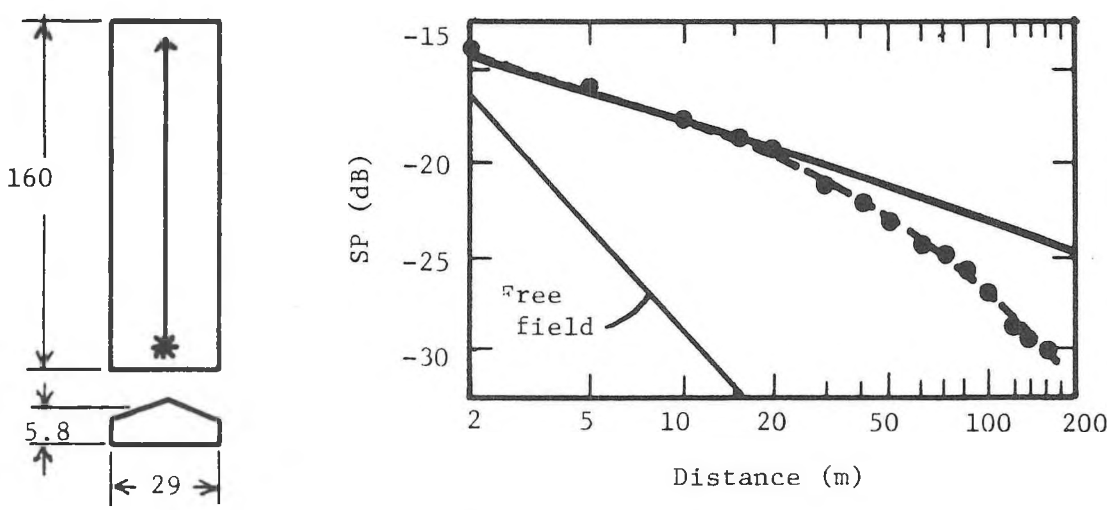


Figure 10. Measured (•) and predicted (—— $Q = 0m^{-1}$; — — $Q = 0.03m^{-1}$) SP at 1kHz in an empty factory as shown at left.

An extreme case of a nominally-empty factory with dimensions of $160m \times 29m \times 5.8m$ is shown in Figure 10. It has also been found that the average absorption coefficient, calculated as above, does not vary much in factories with the same roof construction [20]. For the case of 11 factories with Type A roofs and 5 with Type B roofs, predictions made for the 1kHz octave band using the average calculated absorption coefficient and $Q = 0.03m^{-1}$ gave an average agreement with measured levels of at worst 1.5dB. Use of the absorption coefficient predicted the 1kHz RT to within 0.2s (0.5%) on average. The above procedure is now being extended to factories in which the SP was measured when the factory was empty and fitted. It is hoped to be able to generalise the results and correlate the best-fit Q values with known details of the factory fittings. This should establish an accurate and proven method for predicting SP and RT in empty and fitted factories.

7. CONCLUSION

Research carried out to date has led to a better understanding of the characteristics of, and factors influencing, factory sound propagation and reverberation time. In particular, the influence of factory fittings and roof contour have been elucidated. This understanding has been applied to establish the basic principles and methods for noise control. Important information about the effective absorption of factory surfaces and the scattering cross-section density of factory fittings is being inferred from measurement results; however further research on the estimation and measurement of these quantities is necessary. Scale-modelling techniques applied to factories have been found to be accurate at 1:16 scale; however, the accuracy becomes unacceptably low at the more cost-effective 1:50 scale. Empirical formulae and ray-tracing methods have been used to predict factory sound fields with varied success. An extended Jovicic geometric-acoustic /method-of-images theory has been shown to describe many observed factory-acoustic effects. Comparisons of predictions with results of SP measurements in empty and fitted factories are leading towards the consolidation of a reliable and accurate factory SP prediction method.

REFERENCES

[1] M. R. HODGSON, Theoretical and physical models as tools for the study of factory sound fields. Ph.D. Dissertation, University of Southampton, 1983.

[2] M. R. HODGSON and R.J. ORLOWSKI, Acoustic scale modelling of factories: Part I - Principles, instrumentation and techniques. Submitted to the Journal of Sound and Vibration.

[3] M. HODGSON and R.J. ORLOWSKI, Acoustic scale modelling of factories: Part II - 1:50 scale model investigations of factory sound fields. Submitted to the Journal of Sound and Vibration.

[4] K.H. KUTTRUFF, Sound decay in reverberation chambers with diffusing elements. Journal of the Acoustical Society of America **69** (1981) 1716-1723.

[5] A.M. ONDET, J.L. BARBRY and M. CAFAXE, Etude expérimentale de l'influence de l'encombrement sur les niveaux du bruit dans un local. To be presented at the 12th ICA, Toronto, 1986.

[6] N.C. BAINES and J.S. BOLTON, The effect of angularly varying absorption coefficients on sound fields in disproportionate spaces. Proc. 11th ICA, Paris 1983, Vol. 5, 453-456.

[7] M.R. HODGSON, Measurements of the influence of fittings and roof pitch on the sound field in panel-roof factories. Applied Acoustics **16** (1983) 369-391.

[8] R.J. ORLOWSKI, Predicting noise reduction in factories using scale models. Proc. 11th ICA, Paris (1983) 453-456.

[9] R. FRIBERG, Noise reduction in industrial halls obtained by acoustic treatment of ceilings and walls. Noise Control and Vibration Reduction (1975) 75-79.

[10] M.R. HODGSON, Empirical prediction of sound propagation and RT in factories. Proc. Internoise '83, 595-598.

[11] J.L. BARBRY, A.M. ONDET and M. CAFAXE, Prévision des niveaux sonores dans des locaux comportant des zones d'encombrement différent. To be presented at 12th ICA, Toronto, 1986.

[12] B.M. GIBBS and D.K. JONES, A simple image method for calculating the distribution of sound pressure levels within an enclosure. Acustica **26** (1972) 24-32.

[13] M. GENSANE and F. SANTON, Prediction of sound fields in rooms of arbitrary shape: validity of the image sources method. Journal of Sound and Vibration **63** (1979) 97-108.

[14] J. BORISH, Extension of the image model to arbitrary polyhedra. Journal of the Acoustical Society of America **75** (1984) 1827-1836.

[15] A. L'ESPÉRANCE, G. LEMIRE and J. NICOLAS, Barrier efficiency inside industrial halls via the image approach. Proc. Internoise '85, 491-494.

16 S. JOVICIC, Anleitung zur Vorausbestimmmung des Schallpegels in Betriebsgebäuden. Bericht für das Ministerium für Arbeit, Gesundheit und Soziales des Landes Nordrhein/Westfalen, 1979.

17 E.A. LINDQUIST, Sound attenuation in large factory spaces. Acustica **50** (1982) 313-328.

18 G.R. LEMIRE and J. NICOLAS, Image method prediction of industrial hall noise levels - a new algorithm. Noise Control Engineering (March-April 1985) 58-67.

19 M.R. HODGSON, Accuracy of theoretical and empirical predictions of factory sound fields. Proc. Acoustics '84, Swansea, 381-387.

20 M.R. HODGSON, Towards a proven method for predicting factory sound propagation. To be presented at Internoise '86, Boston.