HOW TO PREDICT FACTORY SOUND PROPAGATION

Murray Hodgson

Department of Mechanical Engineering
University of Sherbrooke, Sherbrooke, Quebec, CANADA J1K 2R1

I. INTRODUCTION

The acoustic's group of the University of Sherbrooke is currently undertaking research on the prediction of factory noise. A reliable factory noise prediction method is a valuable tool. It allows the estimation of worker noise exposure levels and should be an integral part of any prevention programme. It allows noise level to be predicted in, for example, the following cases:
- for new installations, to optimize the building design;
- for different equipment layouts, so that the layout can be optimised;
- without and with noise control measures, to evaluate their effectiveness.

Accurate prediction requires two things:
- a comprehensive accurate predictive model;
- accurate values for the prediction parameters.

This paper discusses current research aimed at developing and validating prediction models and determining the relevant parameters.

The prediction variable used in this work is the sound propagation, defined as follows:

> The Sound Propagation (SP) is the variation with distance from an omnidirectional point source of the sound pressure level (L_p) minus the source sound power level L_w,

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

II. FACTORY-ACOUSTIC PARAMETERS

A comprehensive factory noise prediction model must incorporate the relevant factory acoustic parameters. These parameters are as follows:

GEOMETRY	The positions of the factory surfaces, including barriers and obstacles constituting barriers;
SURFACE PROPERTIES	Factory surfaces absorb and reflect incident sound. Sound absorption is, ideally, described by the impedance, or approximately, by the absorption coefficient. Sound reflection may be more or less specular or diffuse.
CONTENTS	Factories contain a myriad of obstacles which absorb and diffuse propagating sound - the fittings.
SOURCE/ RECEIVER	The sources are characterized by their powers and directivities. The locations of the sources and receivers are important.
AIR ABSORPTION	Can be significant at mid and high frequencies.

In the case of omnidirectional sources, assumed in these studies, in general the unknown parameters are the surface properties and the fitting density.

III. PREDICTION MODELS

Numerous prediction models, based on several theoretical approaches, exist:

Sabine theory [1] - This easy-to-use theory assumes a diffuse sound field; that is, that the factory is empty, quasi-cubic and with uniformly-distributed surface absorption.

Empirical formulae (eg Friberg [2]) - Such formulae are derived from measurement results. They are simple but ignore many important parameters and provide limited frequency information.

Method of images (eg Jovicic [3], Lindqvist [4], Hodgson [5], Lemire and Nicolas [6]) - This approach replaces waves by rays and reflections by image sources. For parallelepiped factories, isotropically-distributed fittings can be considered. The Borish algorithm [7] allows extension to arbitrary shape for empty factories. Arbitrary absorption distributions are incorporated.

Ray tracing (eg Ondet and Barbry [8]) - also assuming rays, this approach involves mathematically sending rays from the sources and following them to the receivers. Arbitrary room geometry, and fitting and absorption distributions are considered.

IV. EMPTY FACTORY PREDICTION

As a first step to investigating factory noise prediction we considered nominally-empty factories - that is, vacant factories with no equipment installed. In this way, in principle, the surface properties could be studied in the absence of fittings. The octave band SP's and reverberation times (RT) were measured in 10 nominally-empty parallelepiped factories. These results were first compared with those predicted by the Sabine theory, by a standard method-of-images model and by ray tracing. At first the fitting density was set to zero (empty factory). Since the absorption coefficients were not known the following procedure was followed: the absorption coefficient, assumed the same or all surfaces, was varied until a best fit with the experimental results was obtained. The conclusions of these predictions were as follows (refer to Fig. 1):

- In the case of quasi-cubic factories, predictions using the absorption coefficients derived from the measured reverberation times using the Sabine theory (the Sabine coefficients) gave good agreement with experiment. In the case of more disproportionately-shaped factories no value of the absorption coefficient gave a good agreement with experiment. Using the Sabine coefficients the Sabine theory underestimated levels at low source/receiver distances and overestimated them at larger distances;

- The method of images and ray tracing gave similar results. In all factories, at most frequencies and for distances up to about 30 m, the Sabine coefficient gave close agreement with experient. At larger distances prediction overestimated levels. The latter result can be explained by hypothesizing that the factories are not truly empty but contain fittings. In general predictions by ray tracing, assuming a uniform fitting density of about $0.03m^{-1}$, gave close agreement with experiment at all distances. The effective fitting density can be explained by the presence of roof beams and surface contouring and objects.

Note that the above results occurred as much at low frequencies, at which geometric-acoustic models are expected to be less accurate, as at other frequencies.

With respect to the accurate estimation of the Sabine coefficients, these do not vary significantly from one factory to another in the case of factories with the same roof construction. Table 1 shows the Sabine coefficients for factories with the following two types of roof: Type A - Double asbestos panel roof, typical of older British factories; Type B - Steel deck roof, typical of newer British and most North American, factories.

TABLE 1 - Octave band Sabine absorption coefficients of two common roof types

FREQUENCY (Hz)	TYPE A	TYPE B
125	0.16	0.10
250	0.10	0.12
500	0.09	0.09
1 000	0.07	0.07
2 000	0.06	0.06
4 000	0.06	0.06

In the case of non-parallepiped factories - such as factories with pitched roofs, common in Britain - the situation is slightly different. As illustrated in Fig. 2, at low frequencies the SP varies with orientation of the measurement axis relative to the roof pitch. Levels along a line parallel to the pitch are generally higher than in the other direction. The effect decreases with increasing frequency and is usually negligible in octave bands above 500 Hz. Predictions using ray tracing, taking account of roof pitch, agree better with experiment than predictions assuming a flat roof - however the agreement is still poor. Thus the roof pitch effect is not purely geometric - it is likely that modal effects are in operation here, though this has yet to be proven.

V. BORISH METHOD OF IMAGES

The standard method of images is limited to parallelepiped factory shape. Borish [7] presented its extension to arbitrary polyhedra. Thus most factory shapes, and factories containing barriers, can be considered, though the method is limited to empty factories.

The principle of the Borish algorithm is simple. Using vector geometry, every image source of every real or image source is found in every surface. Tests are performed on each image-source/receiver ray to determine if the ray represents a real propagation path from the source to the receiver:
- Validity test - do all ray segments reflect from interior surfaces?
- Visibility test - does each reflection occur on the real surface as opposed to its infinite extension in space?
- Obstruction test - is the ray path obstructed?

If an image source passes all three tests it contributes energy to the receiver.

The Borish method has been programmed and run on an IBM-4351-2 mainframe computer. Because of the large number of tests, runtimes are long and maximum image orders of only up to 15 can be achieved in the simplest cases.

Fig. 3 compares octave band SP's measured in a nominally-empty, L-shaped factory with those predicted using the Borish algorithm and the Sabine absorption coefficients. Clearly the agreement is excellent.

VI. FITTED FACTORY PREDICTION

In order to investigate SP prediction in fitted factories - that is factories containing machines, equipment, etc. - and determination of the fitting density, predictions were compared with controlled experiments in idealised scale-model and full-size factories. First it should be mentioned that Jovicic [3] suggested that the fitting density is equal to S/4V, where S is the total fitting surface area and V is the factory volume. It was of interest to investigate the accuracy of this method.

Comparisons were made between predictions made using seven models and experiments, in a parallelepipedic scale model with uniformly-distributed cubic fittings [9], and in a parallepipedic factory containing uniformly-distributed, polystyrene blocks as fittings [8]. For prediction, best-estimate absorption coefficients, and the fitting density calculated from the well-defined fitting surface areas, were used. Fig. 4 shows the results for the full-size factory at 2kHz. The conclusions of these comparisons are as follows:

- the Friberg empirical model and the Lemire and Nicolas model give poor agreement with experiment;
- the Kurze and Jovicic models which ignore side-wall reflections agree poorly with experiment in the fairly narrow, full-size factory;
- the Kurze, Jovicic and Hodgson models agree poorly with experiment at low fitting densities ($Q < 0.05m^{-1}$);
- the Lindqvist model consistently underestimates levels by several dB;
- the ray tracing model agrees well with experiment in all cases.

HOW TO PREDICT FACTORY SOUND PROPAGATION

These results, combined with the fact that this model can account for non-parallelepiped shape and non-isotropic fitting density, show that ray tracing is the most accurate and flexible factory-noise prediction model available.

In order to demonstrate the flexibility of the ray tracing model, Fig. 5 shows noise levels predicted in a factory containing various sources, internal barriers and fitted regions.

It remains to investigate how to estimate the fitting density in real factories. This is currently being done by comparing ray tracing prediction, using the Sabine coefficient, with the octave band SP's measured in 5 factories when first nominally empty and then fitted. Provisional results suggest that the factory fitting density is several times greater than that expected from, for example, the surface areas of rectangular boxes of the same size as the major fittings in a factory. Fitted regions with densities 0.2 - 0.3 m^{-1} are not uncommon.

REFERENCES

[1] W.C. SABINE, Collected Papers on Acoustics, Harvard University Press, Cambridge, 1923.

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

[3] S. JOVICIC, Anleitung zur Vorausbestimmung des Schallpegels in Betriebsgebäuden. Bericht für das Ministerium für Arbeit, Gesundheit und Soziales des Landes Nordrhein/Westfalen, 1979.

[4] E.A. LINDQVIST, Sound attenuation in large factory spaces. Acustica 50 313-328, (1982)

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

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

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

[8] A.M. ONDET and J.L. BARBRY, A model of sound propagation in fitted rooms using a ray tracing technique. Proc. InterNoise 421-424, (1985).

[9] M.R. HODGSON and R.J. ORLOWSKI, Acoustic scale modelling of factories, Part II: 1:50 scale model investigations of factory sound fields, JSV 113 (2) 257-271, (1987).

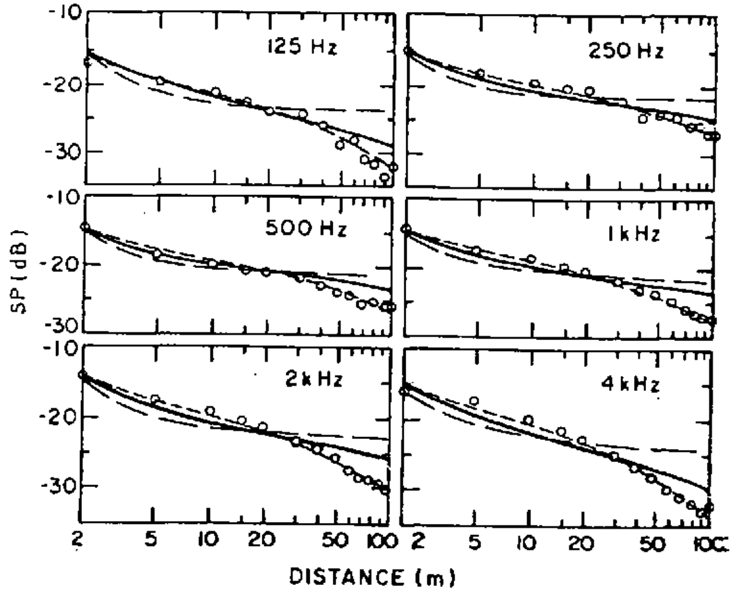


Figure 1 - Octave band sound propagation in a nominally-empty factory (110 m X 31 m X 6.5 m) as measured (O) and predicted by the Sabine theory (— —), and ray tracing (———) with Q= 0 m^{-1}, and by ray tracing (– – – –) with Q= 0.03 m^{-1}.

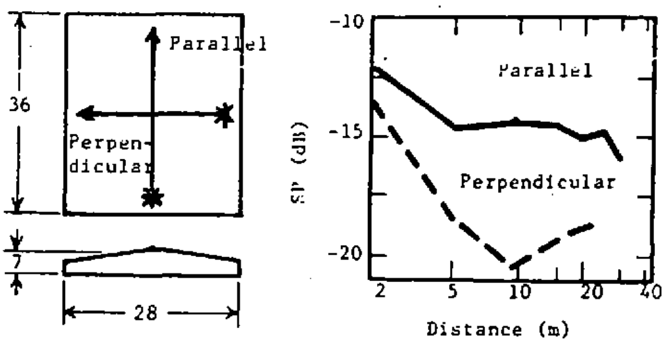
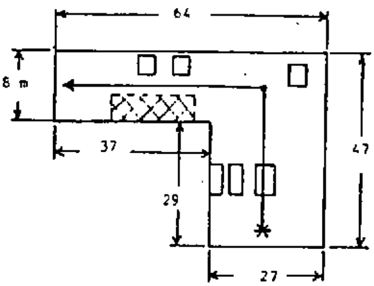


Figure 2 - Sound propagation at 250 H_z measured in two perpendicular directions in a factory with a pitched roof.



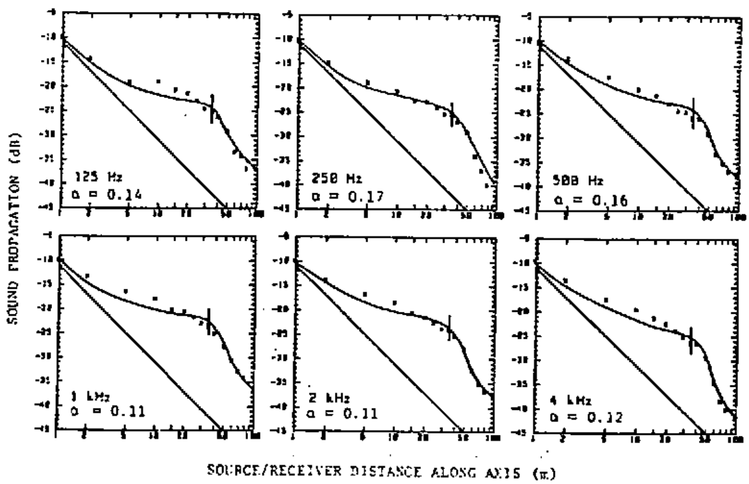


Figure 3 - Octave band sound propagation in an L-shaped factory as measured (x) and predicted by the Borish method (——) using the Sabine absorption coefficients. A large obstacle was located at 5 m ⩽ R ⩽ 10 m.

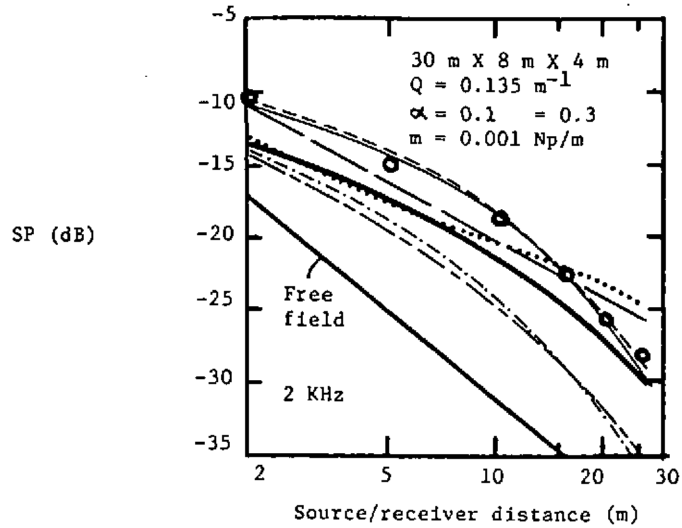


Figure 4 - Sound propagation in a fitted factory as measured (O) and as predicted by the following models:

——— ——— FRIBERG —·—·— JOVICIC ········· LEMIRE

- - - - - HODGSON ——— - — KURZE ▬▬▬ LINDQVIST ——— RAY TRACING

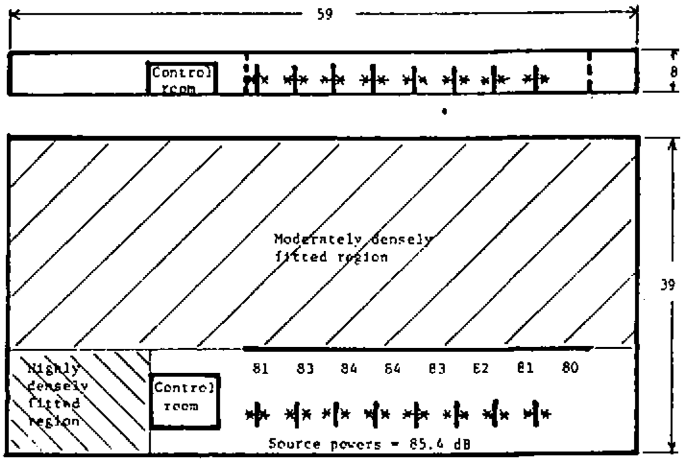


Figure 5 - Noise levels predicted by ray tracing for a factory containing 10 sources, 14 internal barriers and 3 fitted regions.