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PREDICTING FREQUENCY VARYING FITTING DENSITY AND ABSORPTION COEFFICIENT IN INDUSTRIAL WORKROOMS

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1. INTRODUCTION

Industrial workrooms are different from many other rooms in that they are 'fitted'. Fittings have a major effect on the magnitude and spatial distribution of noise levels in an industrial workroom, as well as on the rate of sound decay with time. Analytical models for predicting sound pressure levels in industrial workrooms exist which account for the presence of fittings. There are three main factors which must be considered in fitted rooms, as compared with empty rooms: the fitting spatial distribution (isotropic, localized to a layer on the floor etc.); the absorption coefficient of the fittings; the 'fitting density'. The last two quantities would be expected to vary with frequency. While the orders of magnitude of these two quantities are known, no method is available for determining these quantities directly. Furthermore, theoretical expressions for calculating fitting density assume small fittings and high frequency. Almost all existing prediction models use the Kuttruff fitting density formula [1] to calculate this parameter:

$$Q_0 = S_{tot} / 4\,V \qquad (1)$$

in which Q_0 is the Kuttruff fitting density in m^{-1}, V is the volume of the fitted region in m^3, and S_{tot} is the total surface area of the fittings in m^2. The Kuttruff formula is valid for high frequencies and for small fittings. Note that the quantity $l_f=1/Q_0$ in metres is the mean free-path length between fittings. Lindqvist [2] derived a corrected formula which accounts for the possibility of overlap of fittings of dimension D_f:

$$Q_L = Q_0\,[1 + (8\,Q_0\,D_f / 3\,\pi) - Q_0^2\,D_f^2 / 2] \qquad (2)$$

When the fittings are large, fitting density will increase by 5-10 % after correction by the Lindqvist formula.

2. IMPROVED THEORETICAL EXPRESSIONS

2.1 Fitting Density for Large Fitting Dimension

When the mean free path, $l_{f0}=1/Q_0$, is of the same order of magnitude as, or one order greater than, the fitting dimension, the fitting dimension should be subtracted from the mean free path. That is, $1/Q=1/Q_0-2D_f$. By additionally considering the possibility that a third fitting will block the path between two given fittings - thereby further reducing the mean free path - and combining the new correction with that of Lindqvist - Eq. (2) - an improved fitting-density formula is found as follows:

$$Q' = [(1 / a\, Q_0) - 2\, D_f + 2\, Q_0\, D_f^2]^{-1} \qquad (3)$$

in which $a=1+(8Q_0D_f/3\pi)-Q^2{}_0D_f^2/2$ is the correction factor given by Lindqvist and Q_0 is calculated by Eq. (1).

The effect of the new correction depends on D_f and Q_0. For example, if Q_0=0.1 m^{-1} and D_f=1 m, the fitting mean free path will decrease from 10 m to 8.2 m, and the fitting density will increase to 0.122 m^{-1}, which is 22 % larger than Q_0. As for Eq. (1), Eq. (3) is only valid at high frequency.

2.2 Fitting Absorption Coefficient

In empty rooms the effective mean free path is equal to the room mean free path, $D_{r,eff}=D_r=4V/S_r$, where V is room volume and S_r is room surface area. In fitted rooms, the mean free path will be reduced by a factor exp(-QD_r). The effective absorption of the room surfaces will change from $S_r\alpha_r$ to $S_r\alpha_r/\exp(-QD_r)$. For the same reason, the effective absorption of the fittings will change from $S_f\alpha_f$ to $S_f\alpha_f/\exp(-QD_r)$, with S_f the fitting surface area. The effective fitting absorption coefficient α_f is given by:

$$\alpha_f = [\alpha_{fr}\, (S_r + S_f) - \alpha_{er}\, S_r / \exp(-Q\, D_r)] / [S_f / \exp(-Q\, D_r)] \qquad (4)$$

in which α_{er} and α_{fr} are the average effective absorption coefficients of the empty and fitted rooms, respectively. This formula allows the fitting absorption coefficient to be determined from measured reverberation times in the empty and fitted room.

3. EXPERIMENTAL METHODOLOGY

3.1 Apparatus

Tests were performed in an anechoic chamber and in a test enclosure - both considered as 1:8-scale models. Measurements were made in octave bands from 1-16 kHz (125-2000 HzFS - FS means full-scale equivalent value). In order to model sound propagation in fitted regions, empty 18.9 l mineral-water bottles were used as fittings. These hard-plastic bottles were 40-cm high and 27.5-cm in diameter (3.2 mFS by 2.2 mFS). An anechoic chamber was used as a test environment to approximate an infinite region. Tests were performed in the chamber when empty and when fitted with 81, 162 or 243 bottles corresponding to Kuttruff fitting densities of 0.2 m^{-1} (0.025 mFS^{-1}), 0.4 m^{-1} (0.05 mFS^{-1}), and 0.6 m^{-1} (0.075 mFS^{-1}), respectively. Tests were also done in a 1:8-scale-model industrial workroom. It was 3.75 m (30 mFS) long, 1.875 m (15 mFS) wide, and 0.625 m (5 mFS) high.

3.2. Experimental Determination of Frequency-Varying Fitting Density

By considering the various contributions to the total energy at a receiver position in empty and fitted regions when the source/receiver line is either blocked or not blocked by fittings, the fitting density is found to depend on three measurable quantities which all vary with frequency. Thus, the frequency-varying fitting density is given by:

$$Q(f) = -(1/r) \ln \{1 - [(E_{nb}(f) - E_t(f)] / E_{Q=0}(f)\} \qquad (5)$$

in which r is source/receiver distance, E_{nb} is the sound energy for the case when there is no fitting blocking the direct sound, E_t is the total sound energy, and $E_{Q=0}$ is the sound energy in a free field. Measurements were made in each test band of average values of these quantities at a number of receiver positions in the anechoic chamber fitted with 81, 162 or 343 bottles. These data showed that a non-linear model must be used to express the relationship between fitting density and frequency. After considering several models and applying regression techniques to the experimental data, the best-fit variation of Q with frequency was found to be (with f_0=c/D_f):

$$Q(f) = Q(\infty) / (1 + 1.2\, f_0/f) \qquad (6)$$

3.3 Experimental Validation

Experiments were done in the 1:8 scale-model industrial workroom with an acoustically treated (covered with 50-mmFS-thick glass fibre) ceiling at a height of 5 mFS. The fittings consisted of 31 bottles placed in a uniform distribution on the floor giving Q_0=0.10 mFS^{-1} and Q'=0.18 mFS^{-1}. Fig. 1 compares the measured results at 4000 Hz with those predicted by ray tracing [3] using Q_0 and Q(f). The sound-propagation curves predicted using Q(f) were in excellent agreement with the measured curves at all distances; Q_0 overestimated levels at larger distances.

Comparisons were also made with data from work by Hodgson [4], which involved ray-tracing prediction of sound-propagation curves in a fitted machine shop. The total fitting surface area was 675.5 m^2 giving Q_0=0.16 m^{-1} in the fitted zone. The fitting density of the upper region was considered by Hodgson to be 0.03 m^{-1} with absorption coefficient 0.05. By comparing measured sound-propagation curves with those predicted by ray tracing, Hodgson found that - using a fitting absorption coefficient of 0.1 - the best-fit fitted-region density of 0.23 m^{-1} gave excellent agreement with experiment at all frequencies.

Let us now apply the Eq. (3) to the above data. The mean fitting dimension was calculated to be 1.15 m corresponding to Q'=0.255 m^{-1}. This is similar to the value of 0.23 m^{-1} found by the best-fit method. The 125-2000 HzFS frequency-varying fitting densities Q(f) calculated from Eq. (6) are 0.10, 0.14, 0.18, 0.21 and 0.23 m^{-1}, respectively. By comparing measurement and prediction for different values of fitting absorption coefficient, the octave-band best-fit values were found to be 0.20, 0.15, 0.12, 0.10 and 0.10, respectively. The 500-HzFS measured and predicted sound-propagation curves are compared in Fig. 2. Also shown is the curve predicted using the fitting density of 0.23 m^{-1} and fitting absorption coefficient 0.1. The agreement between the three curves was excellent at all frequencies and distances. The agreement with experiment is as good using Q(f) and the best-fit, frequency-varying fitting absorption coefficients as that obtained by Hodgson using constant fitting absorption coefficient 0.1 and constant fitting density 0.23 m^{-1}. Since fitting absorption coefficient cannot at present be measured directly, it is not possible to say which set of prediction parameters best represents reality - only that they give equally good agreement with experiment.

Next let us calculate the fitting absorption coefficient using Eq. (4) - modified for the case of two fitting zones. Note that Hodgson [4] presented "empty-room" and effective "fitted-room" surface-absorption coefficients for the machine shop, the latter calculated from the measured reverberation times in the fitted room as if the room were empty. The octave-band fitting absorption coefficients for the fitted zone calculated using these values in Eq. (4) are 0.21, 0.14, 0.09, 0.11, and 0.10, respectively. These values are very similar to those determined by the best-fit method.

If we use the constant fitting density 0.23 m^{-1} found by Hodgson [4], the octave-band fitting absorption coefficients become 0.061, 0.059, 0.056, 0.10 and 0.10, respectively. The values at 2000 and 4000 Hz are exactly equal to the results obtained by the best-fit method, but the first three values are significantly smaller. This suggests that fitting densities must vary with frequency.

[1] H. Kuttruff, *Acustica* **18**, 131-143 (1967).
[2] E. A. Lindqvist, *Acustica* **50**, 313-328 (1982).
[3] A. M. Ondet and J.-L. Barbry, *J. Acoust. Soc. Am.* **85**(2) 787-796 (1989).
[4] M. R. Hodgson, *Noise Control Engineering Journal* **33**, 97-104 (1989).

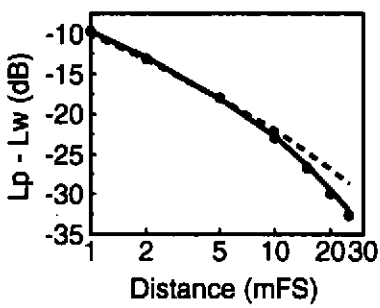

Fig. 1. 4000-HzFS octave-band sound-propagation curves in the 1:8 scale-model workroom as (●) measured and as predicted using fitting densities of (- - - - -) 0.10 m-1 and (———) 0.18 m-1.

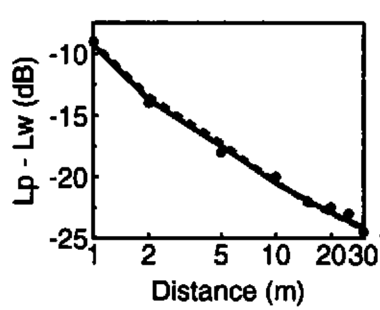

Fig. 2. 500-Hz octave-band sound-propagation curves for the machine shop as (●) measured and as predicted using fitting densities / absorption coefficients of (———) 0.23 m-1 / 0.1, and (- - - - -) 0.14 m-1 / 0.15.