IMPROVED METHODS FOR ESTIMATING FITTING DENSITY AND FITTING ABSORPTION COEFFICIENT IN INDUSTRIAL WORKROOMS

Murray Hodgson and Ke Li

Occupational Hygiene Programme and Department of Mechanical Engineering
University of British Columbia, 3rd Floor, 2206 East Mall, Vancouver, BC, Canada V6T 1Z4

Introduction

When predicting noise in industrial workrooms, a major factor that must be taken into consideration is the presence of 'fittings' - obstacles such as machines and stockpiles - in the room. Besides the fitting spatial distribution, there are two important parameters used in prediction models to describe the fittings. One is the fitting density - a measure of the number of fittings and of the average fitting scattering cross-sectional area - and the other is the fitting absorption coefficient. While ranges of typical fitting densities and absorption coefficients are known, no reliable method exists for measuring or estimating them in a given case. Furthermore, theoretical expressions for calculating fitting density assume small fittings and high frequency. In particular, Kuttruff proposed - assuming spherical fittings - that:

$$Q_0 = S_{tot} / 4\,V \tag{1}$$

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. Lindqvist [2] corrected for the possibility of overlap of fittings of dimension D_f; the Lindqvist fitting density is:

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

When the fittings are large, fitting density will increase by 5-10 % after correction by the Lindqvist formula. The aim of the research discussed here was to develop and test improved methods for determining fitting density and absorption coefficients in industrial workrooms.

Correction for Large Fitting Dimensions

By considering the possibility of a third fitting blocking the path between two others, a formula was derived for calculating the fitting density in the case of large fitting dimension:

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

in which $a=1+(8Q_0D_f/3\pi)-Q^2{}_0D_f{}^2/2$ is the Lindqvist correction factor in Eq. (2) and Q_0 is calculated by Eq. (1). The effect of the new correction depends on D_f and Q_0. If Q_0=0.1 m^{-1} and D_f=1 m, the fitting density will increase to 0.122 m^{-1}, which is 1.22 Q_0. Again, Eq. (3) is only valid at high frequency.

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:

$$Q(f) = -\,(1/r)\,\ln\,\{1 - [(E_{nb}(f) - E_t(f)] / E_{Q=0}(f)\} \tag{4}$$

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 the 125-4000 Hz octave bands, of average values of these quantities at a number of receiver positions in an anechoic chamber fitted with 81, 162 or 343 non-absorptive mineral-water bottles, all considered as 1:8 scale models. 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):

$$Q(f) = Q(\infty) / (1 + 1.2\,f_0/f) \tag{5}$$

Fitting Absorption Coefficient

A formula for fitting absorption coefficient was derived:

$$\alpha_f = [\alpha_{fr}\,(S_r + S_f) - \alpha_{er}\,S_r / \exp(-Q\,D_r)] / [S_f / \exp(-Q\,D_r)] \tag{6}$$

in which α_{er} and α_{fr} are the average effective absorption coefficients of the empty and fitted rooms, respectively, calculated from measured reverberation times using diffuse-field theory, and D_r is the room mean free path $4V_r/S_r$. S_r and S_f are the room and fitting surface areas, respectively.

Experimental Validation

To validate the new expressions, experiments were done in a fitted 1:8 scale-model room with an acoustically treated ceiling. The fittings consisted of 31 mineral-water bottles placed on the floor giving Q_0=0.10 mFS^{-1} and Q'=0.18 mFS^{-1} (FS=full scale). The sound-propagation curves predicted by ray tracing [3] 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. 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 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 Hz frequency-varying fitting densities calculated from Eq. (5) were 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 agreement with experiment was 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 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. (6) - modified for the case of two fitting zones. Hodgson [4] presented "empty-room" and effective "fitted-room" surface-absorption coefficients for the machine shop. The octave-band fitting absorption coefficients for the fitted zone calculated using these values in Eq. (6) are 0.21, 0.14, 0.09, 0.11, and 0.10, respectively. These values are very similar to the best-fit values.

If we use the constant fitting density of 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.

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[3] A. M. Ondet and J.-L. Barbry, *J. Acoust. Soc. Am.* **85**(2) 787-796 (1989).
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