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Prediction of sound-pressure level in an occupied enclosure

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In a room with inadequate sound absorption, occupants may suffer from low speech intelligibility due to the high noise level resulting from human activities. For effective communication, they tend to raise their voices. In the present study, a method which takes into account the effect of raising voices is derived to predict the variation of A-weighted sound level inside an enclosure in which the number of occupants changes with time. Site measurements are also performed in a canteen of capacity around 250. The model predicts the variations of A-weighted sound levels with a number of occupants with sufficient accuracy for engineering applications. © *1997 Acoustical Society of America.* [S0001-4966(97)05605-1]

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INTRODUCTION

When people speak freely in an enclosure, the average A-weighted sound level inside the enclosure increases as the number of people increases. However, this growth in noise level gradually interferes with dialogue, and lowers the speech intelligibility. To preserve the latter, the people have to raise their voices. This is a positive feedback, since the people keep on raising their voices, resulting in a rapid increase in the A-weighted sound level inside the enclosure. This ''cocktail party effect'' was first discussed by Pollack and Pickett.[1] MacLean[2] proposed a theory to explain this effect but his model involves grouping of occupants, where in reality the group size cannot be determined. The rise in voice level is also not considered in his theory. Legget and Northwood[3] conducted noise surveys in cocktail parties, but no suitable method for predicting A-weighted sound level was found. Very often, this ''cocktail party effect'' is ignored in practice, resulting in overdesign for absorption or failure to achieve an acceptable acoustical environment.

For the design of an acceptable indoor acoustical environment, the variation of A-weighted sound level with the number of people inside the room is required. In this study, a method is derived to predict the A-weighted sound level in an occupied enclosure. It includes a simple model for elevation of the human voice and the effect of sound absorption inside the enclosure. Site measurements were also conducted to test the proposed A-weighted sound level prediction method.

I. THE SOUND LEVEL PREDICTION MODEL

The A-weighted sound-pressure level (SPL) in an enclosure due to a sound source of power W can be estimated by the following well-known formula:

$$\mathrm{SPL}=10\log_{10}\left(\frac{W}{W_0}\right)+10\log_{10}\left(\frac{Q}{4\pi r^2}+\frac{4}{R}\right), \qquad (1)$$

where $W_0=10^{-12}$ W, Q is the directivity of the source, R is the room constant of the enclosure, and r is the distance between the observer and the sound source (for instance, see Ref. 4). The resultant A-weighted sound level from n sound sources at the position of the jth occupant is thus given by

$$\mathrm{SPL}_j=10\log_{10}\left[\sum_{i=1}^{n}\frac{W_i}{W_0}\left(\frac{Q_i}{4\pi r_{ij}^2}+\frac{4}{R}\right)\right], \qquad (2)$$

where the suffix i denotes the quantity associated with the ith sound source (that is, the ith occupant), and r_{ij} denotes the distance between the ith and the jth occupants.

In this model, the sound in the enclosure is assumed to be solely due to human voices. Human voice may have a particular directivity pattern such that Q_i in general is not unity. However, in the situation modeled, the orientations of the human faces in the enclosure (and thus the voice directivity) are expected to be random. This randomness makes it reasonable to treat Q_i as unity on average. Other values of Q_i do not appear to be justified.

The room constant R changes with the number of people inside the enclosure. If R_0, S, and A_p are the room constant of the empty enclosure, the total surface area and the average sound absorption area of each occupant, respectively, the absorption area of the empty enclosure A_0 is given by the expression

$$R_0=\frac{A_0}{1-A_0/S}\Rightarrow A_0=\frac{R_0}{1+R_0/S}, \qquad (3a)$$

and the total absorption area in the enclosure including the presence of n persons is A_0+nA_p. The room constant R when there are n persons present can be approximated by the following formula:

$$R=\frac{A_0+nA_p}{1-(A_0+nA_p)/S}=\frac{R_0+nA_p(1+R_0/S)}{1-(nA_p/S)(1+R_0/S)}. \qquad (3b)$$

Here, A_p is taken to be 0.44 m^2 in the following numerical computation.[5]

For normal conversational speech without raised voices, the A-weighted sound power level W is estimated from the speech spectrum shown in Fig. 13.3 of Kinsler and Frey[6] and the A-weighting attenuation curve given in Sharland.[7] The estimated A-weighted sound level at 1 m from the human mouth is about 62.5 dB. As a speech power level of 73 dB gives an overall sound-pressure level of 65 dB at 1 m from the human mouth,[8] W is taken to be 70 dB for all occupants. However, it is not known exactly what A-weighted sound level will trigger the raising of voices, and a theoretical formulation of how people raise their voices according to surrounding noise level does not currently exist. It is proposed in the present study that if the people start raising their voices at an A-weighted sound level of SPL_r dB, they have to produce a sound level that at least keeps the difference between their voice level and the surrounding noise level unchanged during the raising of voices. Therefore, the sound power level generated by the ith occupant W_i is estimated using the relationship

$$10\log_{10}\left(\frac{W_i}{W_0}\right)-70=\mathrm{SPL}_i-\mathrm{SPL}_r \quad (4)$$

for $\mathrm{SPL}_i \geqslant \mathrm{SPL}_r$. The increase in W_i further increases the A-weighted sound level in the enclosure, and thus may result in further increase in W_i as other occupants may raise their voices at the same time. The A-weighted sound level at each occupant position is then calculated using Eq. (2) and iteration continues until the voice power level of each occupant converges (less than 0.1 percent change in two consecutive iterations).

The last parameter required for the prediction of A-weighted sound level is r_{ij} [Eq. (2)]. In reality, r_{ij} cannot be exactly measured due to the randomness of occupancy pattern, unless the capacity of the enclosure is reached. In the present study, the enclosure is modeled as a rectangular mesh and each occupant occupies one small rectangle of this mesh. The predicted A-weighted sound level discussed in the present study is calculated at the center of this mesh, such that

$$r_{ij}=\sqrt{\{[j-(m_c-1)/2]\Delta_c\}^2+\{[i-(m_r-1)/2]\Delta_r\}^2}, \quad (5)$$

where $m_r \times m_c$ is the mesh size (odd numbers), Δ_r and Δ_c the row and column widths in the mesh, respectively.

Since the actual occupant location pattern is not known, the predicted A-weighted sound level does not directly reflect the dynamic variation of A-weighted sound level due to occupancy. It is known that the sound pressure varies with the reciprocal of spatial separation; the highest growth rate of A-weighted sound level at the mesh center occurs when the rectangles closest to the mesh center are occupied first and occupancy occurs gradually outwards from mesh center. That is, calculation commences with the eight rectangles surrounding the mesh center occupied first. Then, the next innermost set of unoccupied rectangles (outside the first eight occupied rectangles) are occupied, and calculation is repeated. This procedure is repeated until all the rectangles are filled up. The results calculated in this manner form the upper bound of the A-weighted sound level. Similarly, the slowest increase in sound level occurs when the rectangles at the perimeter of the mesh are occupied first and occupancy moves toward the mesh center, layer by layer. A lower bound of A-weighted sound level is thus obtained. The actual A-weighted sound level in the enclosure should lie within these two boundaries.

II. SITE MEASUREMENT SETUP

Site measurement results were obtained in the staff canteen of the Hong Kong Polytechnic University, which has a capacity of around 250 and dimensions of 21 m×21 m×2.8 m high. The average separation of the occupants is about 1 m. A canteen is chosen for the present study because the noise inside it is primarily due to human voices, and there is a rapid change of occupant number within a relatively short period of time. For the measurement, a computer program was developed so that the number of people going into and out of the canteen could be logged into a notebook computer. The corresponding time of people going in and out of the canteen was also recorded by this program using the built-in clock of the notebook computer.

The equivalent sound-pressure level L_{eq}, and the A-weighted level exceedance L_{10} and L_{90} were recorded every 1 min using a calibrated Metrosonic db3100E integrating sound level logger. The built-in clocks in db3100E and the notebook computer were matched before the start of each measurement. The location of the A-weighted sound level measurement was far away from walls and at ear height. Each measurement was done within busy hours and in general lasted for 3 h. Four site measurement trials were carried out in the present study, so as to reduce the impact of random occupancy pattern on the measured A-weighted sound levels.

The room constant of the empty canteen is estimated from the measured reverberation time using Sabine's equation.[4] The reverberation time was measured using a Brüel & Kjær 2236C precision sound-level meter and Brüel & Kjær 2144 dual channel frequency analyzer in the multispectrum mode with averaging time of 1 ms. The sound was generated using a JBL 4604B 20-in. loudspeaker with a white noise signal fed to the loudspeaker through a power amplifier. Four measurements were done with different sound level meter locations, but the difference in the reverberation times obtained in these measurements is insignificant. The average reverberation time for the unoccupied canteen is 0.47 s, giving a room constant R_0 of 680.7 m^2. The decay curves from the reverberation time measurements also show the presence of flutter echo between parallel walls in the canteen. This canteen is not a very reverberant space. The large sound absorption in the canteen is probably due to the furniture, an open door, measuring 2 m×1 m, and the acoustical suspended ceiling having an NRC of 0.95. Other surfaces of the canteen are either painted concrete, glass windows, or concrete floor covered with plastic tiles, which are reflective. Although the canteen may not be very symmetrical acoustically, which makes the application of Eq. (1) questionable, the point is whether the error induced, if there is any, is within engineering tolerance or not. This will be discussed later.

III. EXPERIMENTAL RESULTS AND COMPARISONS WITH PREDICTIONS

Figure 1 is a typical example showing the time variations of occupant number n, and L_{eq}. These variations appear to be very similar to each other. The sound levels increase as the occupant number n increases. However, abrupt

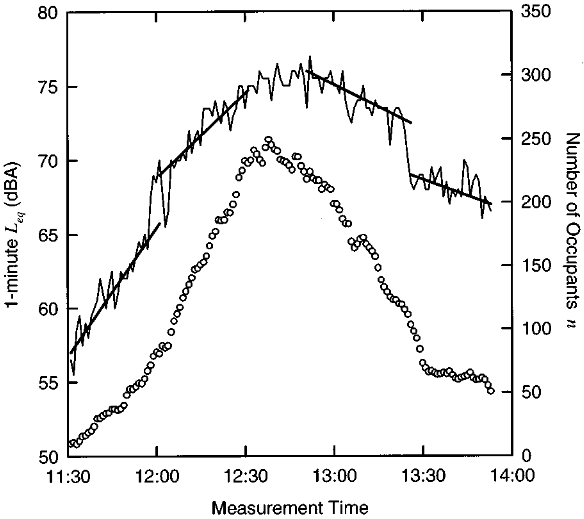

FIG. 1. Time variations of occupant number and A-weighted sound level. Thin continuous line: L_{eq}; thick straight lines: mean variation lines; ○: occupant number.

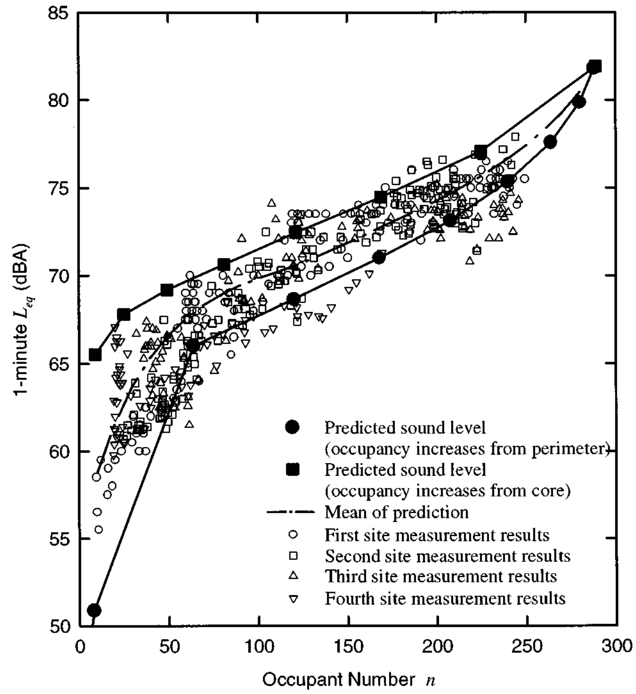

FIG. 2. Comparison of predicted and site measurement results. ●: Predictions with occupant number increases from perimeter; ■: predictions with occupant number increases from core; —·—: mean values of predictions from the two occupant number increase modes; ○: first site measurement results; □: second site measurement results; △: third site measurement results; ▽: fourth site measurement results.

changes of L_{eq} occur at the time 12:00 and 13:23. The gradual variations of occupant number at the times of these abrupt changes in sound level suggest that the first abrupt increase in L_{eq} is due to the raising of human voices, while the other discontinuity results from the restoration of normal voice output. It is noted from Fig. 1 that discontinuities, both in slope and trend, occur at L_{eq} around 65 dB and 73 dB for the increasing and decreasing occupant number cases, respectively. Such a phenomenon basically appears in all trials (not shown here). However, for simplicity, it is more desirable to assume a single L_{eq} at which voice output is raised, because the actual mechanism which determines the raised voice level is still not well understood. It is therefore assumed in the prediction model that the occupants raise their voices when an A-weighted sound level exceeding 69 dB (mean of 65 dB and 73 dB) is heard. This 69 dB A-weighted sound level is also approximately equal to that just after normal voice is restored (Fig. 1), suggesting further the possibility of humans raising their voices at around this noise level. Thus, $\mathrm{SPL}_r = 69\,\mathrm{dB}$.

Although Fig. 1 suggests that L_{eq} depends not only on the number of occupants but may also depend on whether this number is increasing or decreasing, the difference in L_{eq} in these ''increasing'' and ''decreasing'' occupant number modes is not significant in view of the large randomness in occupancy pattern (not shown here). Therefore, data from these two modes are not separately considered in the rest of the discussion. Owing to the large degree of scattering in the site measurement data, the variation of noise climate with occupant number is not discussed.

Figure 2 gives a comparison between the site measurement results and the predictions using Eq. (4). A 17×17 mesh is used in the calculations. It is assumed that human beings raise their voices when the A-weighted sound level exceeds 69 dB. Over 90 percent of the site measurement results fall within the predicted A-weighted sound level boundaries. Although sophisticated occupant distribution statistics are not obtained,[8] the mean value of the two computed boundaries seems to give a reasonably good estimation for the variation of A-weighted sound level inside the enclosure. In order to test how well the predicted mean A-weighted sound level variation fits the experimental data, a hypothesis testing using the student t test was performed. The present situation is the same as that in the case of ''matched pairs'' illustrated in Hoel.[9] The null hypothesis is that the mean of the differences between the predicted and experimental results vanishes. While the correlation coefficient between the predicted and experimental results is 0.91, the so calculated t value is 1.96, giving a probability ≈ 0.05 and suggesting that there is no significant difference between the two sets of results at the 95 percent confidence level. In view of the relatively high uncertainties in the human voice power level and the critical A-weighted sound level that triggers the raising of voices, the present model gives reasonable estimates of the A-weighted sound levels in the canteen.

A large scattering of data is observed for occupant number $n < 50$. It is probably due to granularity of where people sit, not all of them talking at the same time, and the relatively large difference in individual voice power levels at small n (such that the measured A-weighted sound levels depend substantially on measurement location). When n becomes large, this randomness is smoothed out. It is also noted from Fig. 2 that there is a tendency for lower rate of increase of A-weighted sound level with n for $n > 250$, suggesting that the present model may significantly overestimate the A-weighted sound level at large occupant numbers. This also suggests that there is an upper limit of voice power level, although this could not be estimated from the present site measurement results.

It is also found that an over 30 percent change in A_p results only in less than 1-dB difference in the predicted A-weighted sound level for $n \leq 200$, showing that the method does not depend very much on A_p in the present situation.

In view of practical use of the proposed sound level prediction method, the base room sound absorption of an enclosure can be estimated once the capacity and function of the enclosure are known. The function of the enclosure determines the maximum allowable A-weighted sound level, while its capacity is used to determine the mesh size in the prediction method whose algorithm is depicted in Sec. II. Optimum room absorption can then be found by iteration. However, further investigation is needed to test the robustness of the prediction model.

IV. CONCLUSIONS

A method incorporating the increase of voice power level is proposed in the present study for the prediction of the A-weighted sound level inside an enclosure in which the number of occupants varies with time. Site measurements were conducted in a canteen to validate the prediction method. Reverberation time measurements are also performed in a canteen to facilitate comparison between predictions and measured results.

Results of the present study tend to indicate that the occupants raise their voices when the A-weighted noise level exceeds 69 dB and suggest that the prediction method, despite its simplicity, gives good estimates for the upper and lower limits of the A-weighted sound level inside an occupied enclosure. Although an exact estimation of the A-weighted sound level cannot be done because of the large randomness in occupancy pattern, the mean values of the two mentioned A-weighted sound level limits give, allowing for scattering, a satisfactory estimate of the A-weighted sound level.

It should be noted that the present model is limited to one, highly absorptive, space, and the raised voice threshold in this study was chosen empirically and thus may be specific to the present experimental condition. Further investigations into the subject are needed before the present prediction method can be extended to enclosures of other functions.

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