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A DISTRIBUTION FUNCTION APPLICABLE TO OFFICE NOISE STUDY

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Noise measurements were performed in 27 air-conditioned landscaped offices in the present investigation. From the measured equivalent sound pressure levels, percentile levels and noise level cumulative distributions, it is found that linear relationships exist between percentile levels and the equivalent sound pressure level. A new distribution function is proposed in the present study to describe the cumulative distribution as well as the probability density function of noise in air-conditioned landscaped offices. Higher order moments of the noise statistics can then be found. Results also enable the estimation of the above noise statistics from equivalent sound pressure levels and will be beneficial to the evaluation of existing offices and the setup of specifications for new commercial offices.

1. INTRODUCTION

Together with a worldwide growth of economy, there is a quest for better indoor environments by the general public nowadays spend most of the time inside buildings. Noise control is one of the essentials for the creation of a comfortable indoor environment as noise has significant effect on human beings [1].

The study of noise has a long history. Over the past few decades, research has been carried out to study traffic noise and noise inside offices (for examples, see references [2] and [3]). Many different noise criteria have been proposed but the selection of suitable noise criteria for use in setting up noise standards remains a very controversial issue. Beranek [4] proposed the use of the noise criterion curves (NC). Some researchers think that low frequency noise is very important [5] while there is suggestion that a balance of noise spectral content should be carried out [6]. However, among the indices or parameters proposed so far, NC and the equivalent sound pressure level L_{eq} are the two chosen for application in environmental noise control and building design [7, 8]. The former sets the noise level limits in octave bands from 63 Hz to 8 kHz and the latter represents the average sound energy received during the measurement period. Details of these noise indices can be found in existing literature such as Harris [9]. Their advantages, especially that of L_{eq}, are simply that they can be measured *in-situ* and are easy to interpret.

There has been rigorous research in traffic noise characteristics. Kurze [10] showed theoretically that the noise from a continuous passage of vehicles follows a Pearson Type III distribution. This distribution, which is also called the gamma distribution in statistics, is often used to describe distributions that have low probabilities for intervals close to zero, with the probability increasing to a certain value as the interval moves in the positive direction and then decreasing gradually as the interval moves out even further. Details of this special continuous distribution can be found in some textbooks (for instance, Wilks [11]) and thus are not repeated here. Kurze [10] also gave measurement results to

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supplement his findings. Another interesting finding is from Burgess [12] who showed that there exists an approximately linear relationship between L_{eq} and the percentile level L_{10} in traffic noise. Percentile level L_N represents the sound pressure level which is exceeded for N% of the measurement time and thus L_{10} denotes a somewhat high level [9]. The results of Burgess [12] suggest that for traffic noise in Australia a prediction of L_{10} within engineering tolerance is possible once L_{eq} is known.

Noise in offices, especially those which are air-conditioned, are gradually attracting more attention. Keighley [3] attempted to set up acceptability criterion for office noise. Hay and Kemp [13, 14] made noise measurements inside air-conditioned offices. However, their studies were done in the 70's and their results may no longer be applicable to the present situation. The more important aspect is that they had not made an attempt to try to recognize or uncover the characteristics of office noise. The recent results of Tang and Chan [15] suggest the existence of relationships between weighted sound levels and between NC and L_{eq}. This seems to imply that noise level fluctuations in air-conditioned offices may have definite characteristics. It has yet to be investigated whether statistical characteristics, like that of Kurze [10] for traffic noise, can be found in office noise. The results obtained from a survey in air-conditioned landscaped offices of Tang [16] illustrate that L_{eq} gives the best correlation with human acoustical sensation among the other commonly used noise indices. It is thus also interesting to study how the office noise characteristics are related to this simple and ready-to-measure L_{eq}. If such relationship exists and is established, the data collection requirements for the evaluation of the acoustical environment for existing offices can be reduced. Also, the specification of a single L_{eq} in the design stage will then give engineers and acousticians some ideas of the noise fluctuation characteristics so that simpler specification for acoustical environment is possible. In the present study, over one thousand noise measurements were made in 27 modern air-conditioned landscaped offices. It is hoped that a clear and well defined office noise statistics can be found.

2. NOISE MEASUREMENT AND SPECTRAL RESULTS

In the present study, noise measurements were carried out in twenty seven modern air conditioned landscaped offices in commercial buildings of less than eight years old. The selection of office buildings for the present study was in general, random. However, there were office managers who refused to carry out the survey so 27 offices were found in the site search. The air-conditioning systems found in these offices were mainly of the constant and/or variable air volume type. Fan coil units were also found. These systems are the most common types found nowadays and thus the results so obtained should provide a reasonable average picture of the noise levels inside modern air-conditioned offices. It is not intended to look at noise levels from different types of air-conditioning systems in this study as it has been shown by Tang *et al*. [17] that complaints from office workers have no clear correlation with the type of air-conditioning system installed. Office worker activities in all the surveyed offices are mainly of the clerical type. Inside these offices, carpeted floors, painted walls, walls with wall papers, acoustical ceiling tiles and common clerical tables and chairs were found. This kind of furnishing and decoration is the most common one in modern air-conditioned landscaped offices.

Precision sound level meter Brüel & Kjær 2236C was used to measure L_{eq}, percentile levels (L_{10}, L_{50} and L_{90}) and the cumulative distributions of noise levels at different locations inside the surveyed offices during normal office hours. Each measurement lasted 5 minutes [8]. All locations of noise measurements were close to where the office workers were sitting and were well away from walls and reflecting surfaces. Noise spectra in 1/3 octave bands

TABLE 1

Demographic summary of noise survey

Office	Air conditioning system	Number of measurements	Office	Air conditioning system	Number of measurements
001	Fan coil unit	50	015	Fan coil unit	37
002	Fan coil unit	90	016	Constant air volume	50
003	Fan coil unit	32	017	Constant air volume	17
004	Fan coil unit	71	018	Constant air volume	77
005	Fan coil unit	7	019	Fan coil unit	47
006	Fan coil unit	40	020	Fan coil unit	63
007	Fan coil unit	18	021	Fan coil unit	55
008	Constant air volume	40	022	Fan coil unit	50
009	Constant air volume	60	023	Fan coil unit + Split unit	18
010	Constant air volume	37	024	Constant air volume + variable air volume	28
011	Constant air volume	24	025	Constant air volume	31
012	Variable air volume	27	026	Constant air volume	87
013	Variable air volume	25	027	Constant air volume	102
014	Variable air volume	5			

were recorded by a Brüel & Kjær 2144 dual channel real-time frequency analyzer simultaneously with noise level measurement. A total of 1188 measurements have been made. Table 1 summarizes the demographic details of the present noise survey.

Figure 1 shows some typical noise spectra obtained in office 002, 009, 013 having constant volume, variable volume and fan coil systems respectively. It can be observed that no matter which type of air-conditioning system is installed, the present noise spectra are significantly more broad band than those of Hay and Kemp [14]. This may be due to the advances in technology so that office machines, materials and the air-conditioning systems nowadays are not the same as those in the days of Hay and Kemp [13, 14]. This makes

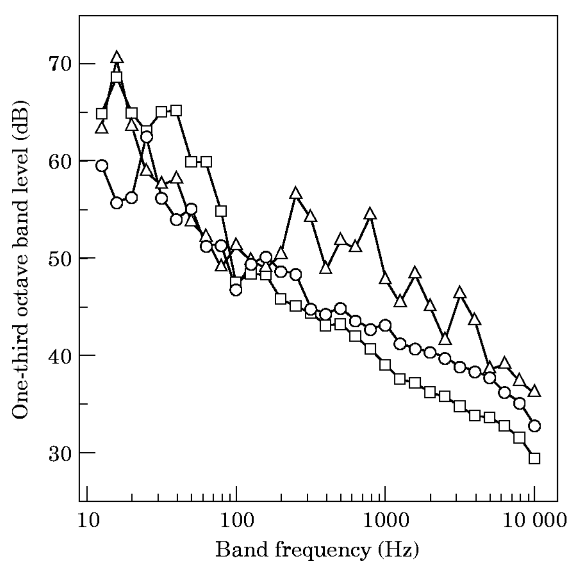

Figure 1. Noise spectra in offices with different air conditioning systems. —○—, Fan coil unit; —□—, constant air volume, —△—, variable air volume.

the present investigation more important. Spectral results have been discussed in Tang and Chan [15]. The present paper focuses on the noise level fluctuation statistics.

3. NOISE LEVEL CUMULATIVE DISTRIBUTION

Results of Burgess [12] illustrate with engineering tolerance that a linear relationship between L_{10} and L_{eq} exists for traffic noise in Australia but did not investigate whether this is a property of the Pearson Type III distribution suggested by Kurze [10]. Figure 2 shows some cumulative distribution curves for noise fluctuation in offices obtained in the present study. Following the presentation of Kurze [10], the abscissa in Figure 2 is the intensity ratio I where

$$I = 10^{(L_N - L_{eq})/10}, \tag{1}$$

and L_N is the percentile level. Cumulative distributions shown in Figure 2 do not suggest the existence of Gaussian distribution as I is not equal to unity at $N = 50$ and there exists substantial asymmetry between data on the two sides of unity intensity ratio. The existence of Pearson Type III noise level distribution also looks questionable (Figure 2). The present office noise distributions seem very much skewed to the side where the intensity ratio is less than 1. The Pearson Type III distribution does not show much skewness. This may be due to the contents and production processes of office noise differing from those of traffic noise.

Though the distribution of office noise level does not seem to follow any well known functions for engineering application, there exists relationships between percentile levels L_5, L_{10}, L_{30}, L_{50}, L_{70}, L_{90} and L_{eq} as shown in Figures 3a–3f. The values of the percentile levels shown in Figures 3a–3f are averages in 0·1 dB L_{eq} intervals. The percentile levels, except L_{10}, L_{50} and L_{90} which were measured through the sound level meter, are estimated from the cumulative distribution curves recorded by the sound level meter. The linear relationship in Figure 3 also appears for other percentile levels not shown in the present

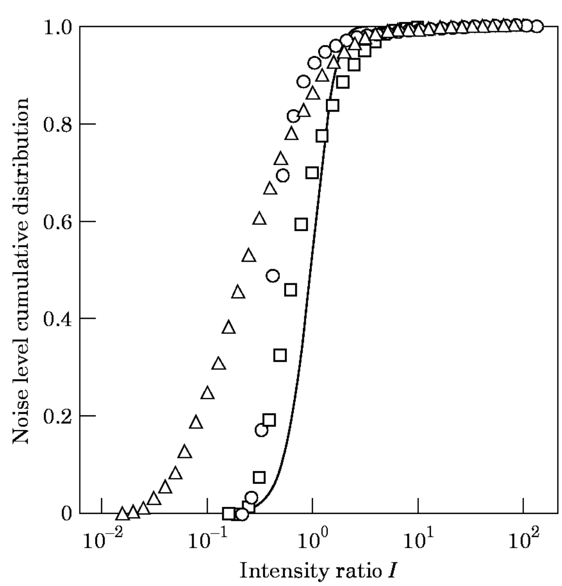

Figure 2. Examples of measured noise level cumulative distributions. —○—, Fan coil unit; —□—, constant air volume, —△—, variable air volume; —, Pearson Type III (Gamma) distribution.

paper. All these linearities are tested against a hypothesis testing procedure incorporated with the Student t-test at 95% confidence level as in Tang and Chan [15]. Similar to the results of Burgess [12] for Australian traffic noise, the office noise data in the presenst study show the existence of strong linear relationship between L_{10} and L_{eq} at least for $L_{eq} < 65$ dBA (Figure 3b). The correlation coefficient r^2 is about 0·98 which is much higher than that of Burgess [12]. Linear relationships basically exist between all L_N and L_{eq} estimated in the present study at least for 45 dBA $< L_{eq} <$ 65 dBA and $N \leqslant 90$, but r^2 decreases with increasing N. For $N = 1$ or 99, the data appear scattered and thus linear relationships between L_1, L_{99} and L_{eq} cannot be established with good confidence here. The regression formulae and r^2 for intermediate values of N studied in the present investigation are tabulated in Table 2. Linear relationships between percentile levels and L_{eq} have not been reported so far in existing literature on office noise studies to the knowledge of the author. The scattering of data at $L_{eq} <$ 45 dBA and at $L_{eq} >$ 65 dBA in Figure 3 are probably due to the small number of observations that make up the data points there. A

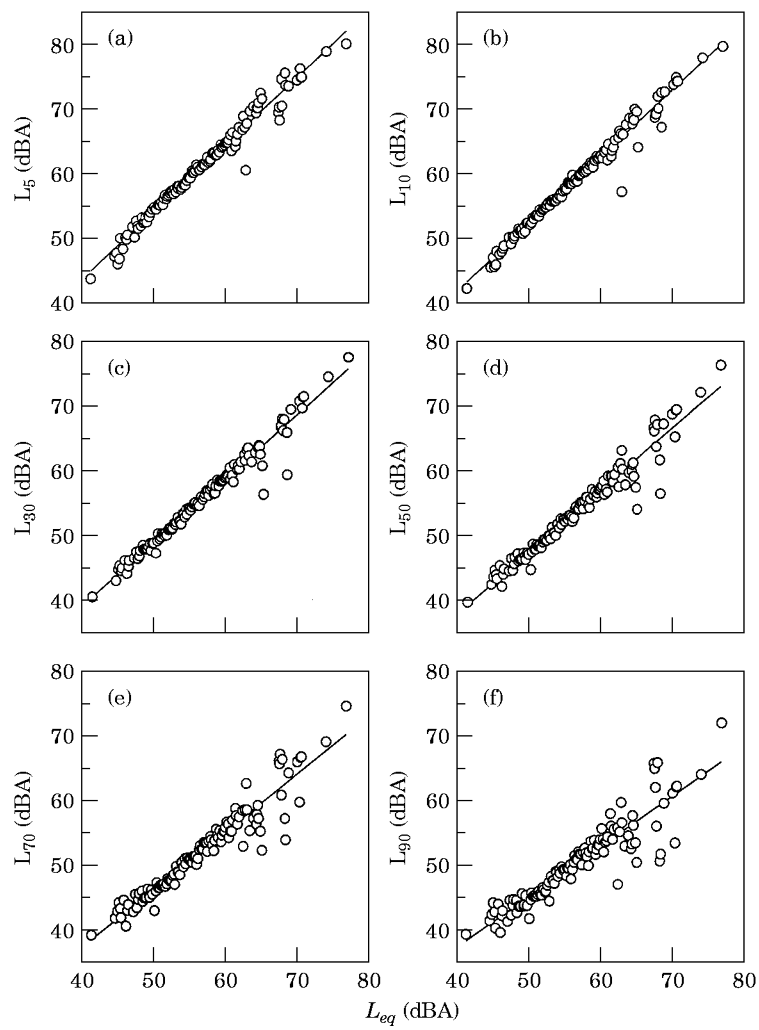

Figure 3. Correlations between percentile levels and equivalent sound pressure level. (a) L_5 ; (b) L_{10} ; (c) L_{30} ; (d) L_{50} ; (e) L_{70} ; (f) L_{90}.

TABLE 2

Summary of correlation between L_N and L_{eq}

N	Regression formula	Correlation coefficient
5	$L_5 = 1{\cdot}0502L_{eq} + 1{\cdot}6367$	0·9759
10	$L_{10} = 1{\cdot}0423L_{eq} - 0{\cdot}0092$	0·9765
20	$L_{20} = 1{\cdot}0210L_{eq} - 0{\cdot}9120$	0·9750
30	$L_{30} = 1{\cdot}0000L_{eq} - 1{\cdot}0377$	0·9693
40	$L_{40} = 0{\cdot}9771L_{eq} - 0{\cdot}7555$	0·9587
50	$L_{50} = 0{\cdot}9514L_{eq} - 0{\cdot}1485$	0·9475
60	$L_{60} = 0{\cdot}9258L_{eq} + 0{\cdot}5319$	0·9345
70	$L_{70} = 0{\cdot}8939L_{eq} + 1{\cdot}5745$	0·9156
80	$L_{80} = 0{\cdot}8519L_{eq} + 3{\cdot}1406$	0·8894
90	$L_{90} = 0{\cdot}7846L_{eq} + 5{\cdot}9000$	0·8498

majority of the present observations falls into the range 53 dBA $< L_{eq} <$ 57 dBA which is higher than the BSI recommendation of 50 dBA for large landscaped offices [8]. It should be noted that though linear relationships between L_N and L_{eq} can be established, linear relationship between linear combination of L_N's, such as the noise climate $L_{10} - L_{90}$, and L_{eq} is not implied (correlation coefficient between noise climate and L_{eq} is found to be 0·33 in the present study). Since results of Tang [16] suggest L_{eq} correlates best with human auditory sensation vote in air-conditioned landscaped offices, the use of noise climate in the setting up of noise criterion for these offices proposed by Keighley [3] looks questionable nowadays.

The existence of linear relationships between percentile levels and L_{eq} suggests that cumulative distribution of air-conditioned landscaped office noise levels can be approximately estimated once L_{eq} is measured. The slopes and intersections of the regression lines shown in Table 2 also have well behaved relationships with L_{eq} as shown in Figure 4. Thus, it seems possible to estimate L_N for any common value of N once L_{eq}

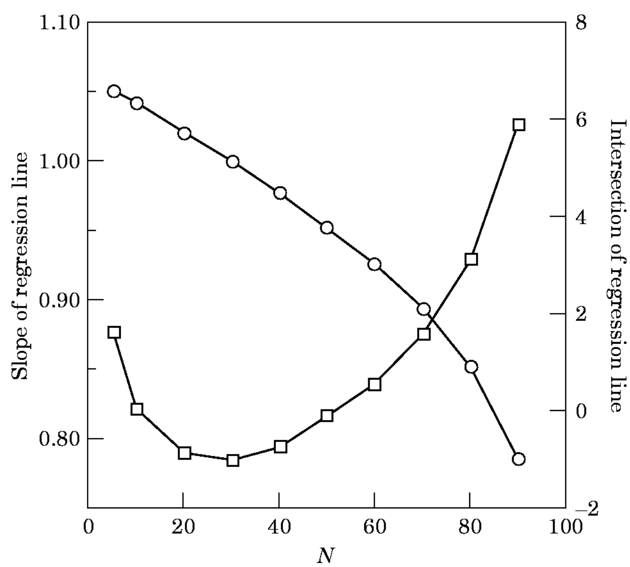

Figure 4. Variation of slopes and intersections of regression lines in Figure 3 with N. —○—, slope; —□—, intersection.

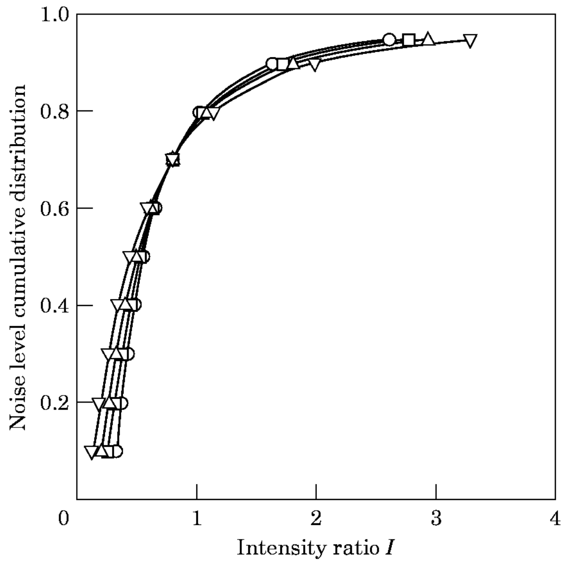

Figure 5. Noise level cumulative distribution from regression results. —○—, L_{eq} = 50 dBA; —□—, L_{eq} = 55 dBA; —△—, L_{eq} = 60 dBA; —▽—, L_{eq} = 70 dBA.

is known. It is noted from Figure 5 that the office noise cumulative distribution curves obtained from the regression analysis for L_{eq} = 50, 55, 60 and 70 dBA are similar to one another but the slope at small intensity ratios increases as L_{eq} decreases. This seems to suggest that the noise distribution becomes slightly less skewed to regions of small intensity ratio as L_{eq} increases.

The method shown in Jessen [18] is employed here to test the confidence level and accuracy of the linear equations shown in Table 2 in estimating L_N with known L_{eq}. This step is important as the validity of the new distribution function developed in the next section for application in modern air-conditioned offices depends significantly on the accuracy of the estimation of percentile levels from the present surveyed sample.

It is assumed that the difference between the predicted and actual percentile levels follows a normal distribution for the whole population. The accuracy, e, of the present prediction formulae in Table 2 can be estimated once the confidence level is fixed using the formulae $e = \pm\tau s/\sqrt{n}$ where s is the sample variance, n the sample size and τ a parameter fixed by the required confidence level [18]. For a population size much larger than 1000, $\tau \approx 1{\cdot}96$ at the 95 % confidence level. Taking the formulae for L_{90} calculation as an example, which is the worst one in the present study (see Table 2), $s = 7{\cdot}2$ dB and since $n = 1188$, e is estimated to be $\pm 0{\cdot}4$ dB. For L_{10}, $s = 1{\cdot}3$ dB and $e = \pm 0{\cdot}1$ dB. e for other L_N falls between $\pm 0{\cdot}1$–$0{\cdot}4$ dB, confirming the validity of the formulae shown in Table 2.

4. DETERMINATION OF NEW DISTRIBUTION FUNCTION

Results from the previous section show that it is possible to estimate the cumulative distribution curve from L_{eq}. This section describes an attempt to determine a suitable mathematical function for the cumulative distribution of air-conditioned landscaped office noise. The data presented hereafter are those estimated from the regression results unless otherwise specified.

It has been discussed earlier and illustrated in Figure 2 that air-conditioned landscaped office noise levels do not follow Gaussian or Pearson Type III distribution. One of the most useful distributions in engineering is that developed by Weibull [19] whose cumulative distribution function F is in the exponential form:

$$F(x) = 1 - \exp\left[-((x-\alpha)/\beta)^{\gamma}\right], \tag{2}$$

where α, β and γ are constants yet to be determined from the sample $\{\mathbf{x}\}$. Though the development of this Weibull distribution has no real scientific or mathematical basis, it is extremely useful in reliability studies and in a wide range of engineering applications [19]. However, it does not seem to fit the present average office noise cumulative distribution curves estimated from regression formulae in Table 2 for $L_{eq} = 50$ dBA and 60 dBA as shown in Figure 6. The value of α can be obtained by using Newton's iteration method and α equals 0·3159 and 0·1851 for $L_{eq} = 50$ dBA and 60 dBA respectively. β and γ can then be calculated using the slope of the straight lines in Figure 6. The misfit of Weibull distribution and the present average office noise cumulative distribution, especially at the low end, also appears for other L_{eq}, showing that noise distribution in air-conditioned landscaped offices is not of the exponential type similar to (2).

The above results seem to indicate that the present noise distribution may not follow the most commonly used functions in engineering statistics. Weibull distribution gives a linear relationship:

$$\log_e(\log_e 1/[1 - F(I)]) = \gamma \log_e(I-\alpha) + \gamma \log_e \beta, \tag{3}$$

where I is the intensity ratio defined by equation (1). With a slight modification of the argument of the Weibull cumulative distribution function and by plotting $\log_e F$ against $\log_e(I) + k_1$ where k_1 is positive so that $\log_e(I) + k_1 > 0$ for $L_{eq} = 50$ dBA, the shape of the curve is more or less similar to that of the flat-hat profile found in jet research (not shown here). Such phenomenon appears also for other L_{eq} between 45 dBA and 65 dBA.

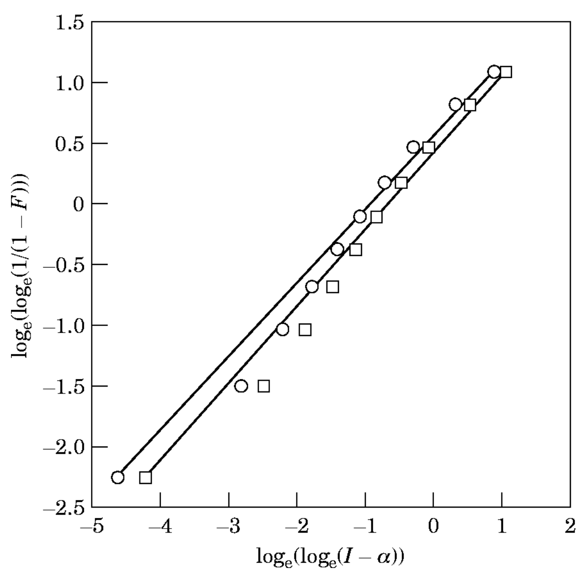

Figure 6. Comparison between regression results and Weibull distribution. ○, Regression results for $L_{eq} = 50$ dBA; □, regression results for $L_{eq} = 60$ dBA. ——, Weibull distribution for $L_{eq} = 50$ dBA; —·—, Weibull distribution for $L_{eq} = 60$ dBA.

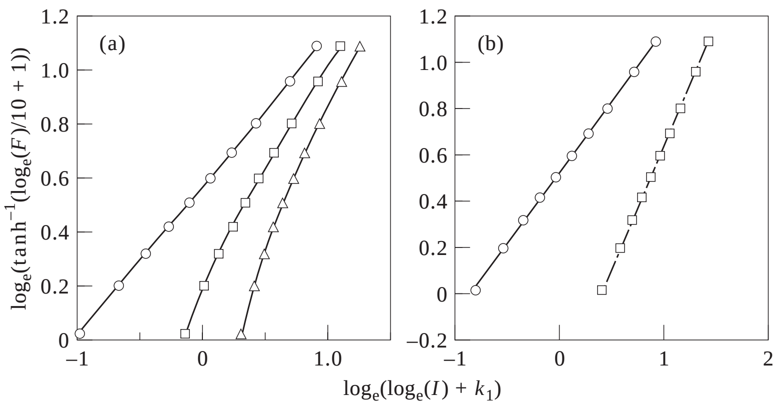

Figure 7. (a) Effect of k_1 on the shape of proposed distribution function (4). —○—, $k_1 = 1{\cdot}5$; —□—, $k_1 = 2$; —△—, $k_1 = 2{\cdot}5$. $k_2 = 10$. (b) Comparison between distribution function (4) and regression results. ○, Regression results for $L_{eq} = 50$ dBA; □, regression results for $L_{eq} = 60$ dBA; —, distribution function (4) for $L_{eq} = 50$ dBA; —·—, distribution function (4) for $L_{eq} = 60$ dBA. $k_2 = 10$.

This favours the use of hyperbolic tangents to fit the present results and thus the distribution function

$$\log_e (F(I))/k_2 + k_3 = \tanh [\Phi((\log_e (I) + k_1))] \tag{4}$$

may be able to describe the present office noise cumulative distribution. Φ and k's are respectively a specific function and constant as yet to be determined. The function Φ must be well-behaved and increases with I. Obviously, $k_3 = 1$ as $\tanh (I) \to 1$ and $F(I) \to 1$ as I tends to infinity. To see whether distribution function (4) fits the present estimated office noise cumulative distribution for $L_{eq} = 50$ dBA, k_2 is arbitrarily chosen to be 10 and $\log_e (\tanh^{-1} (\log_e (F(I))/10 + 1))$ is plotted against $\log_e (\log_e (I) + k_1)$ for $k_1 = 1{\cdot}5$, 2 and $2{\cdot}5$ in Figure 7a. It is noticeable that the shape of the curve depends on k_1. Distribution function (4) will represent the cumulative distribution of office noise data if k_1 takes the value so that the line in Figure 7a is a straight line and then

$$\Phi(\log_e (I) + k_1) = k_5 (\log_e (I) + k_1)k_4. \tag{5}$$

k_4 and k_5 are positive which can be estimated from the slope and intersections of the line. Newton's iteration method is used to determine k_1. The criterion of minimum root mean square deviation of the fitted straight line from the office noise data is adopted in the iteration. For $k_2 = 10$ and $L_{eq} = 50$ dBA, k_1 is around $1{\cdot}575$. The results are illustrated in Figure 7b and it is noticeable that the match is very good at least in engineering tolerance. However, k_1 depends on k_2 even for the same L_{eq}. For every k_2, there exists one k_1 such that the distribution function (4) deviates the least from the estimated noise level distribution as shown in Figure 8. k_4 and k_5 can be calculated once k_1 and k_2 are chosen. Distribution function (4) also matches noise level cumulative distribution at other L_{eq} upon suitable choice of k_2 and k_1 (Figure 7b).

Variation of k_1 with k_2 for $L_{eq} = 50$ dBA and 60 dBA are shown in Figure 9. It can be noted that k_1 increases rapidly with small k_2 but varies slowly with large k_2. For $I \to 0$, the value of the hyperbolic tangent tends to -1 and therefore k_2 needs to be very large so that $F(I) \to 0$. The present distribution function (4) does not seem to be very valid for infinitesimal intensity ratios but this range of sound pressure does not in general exist in

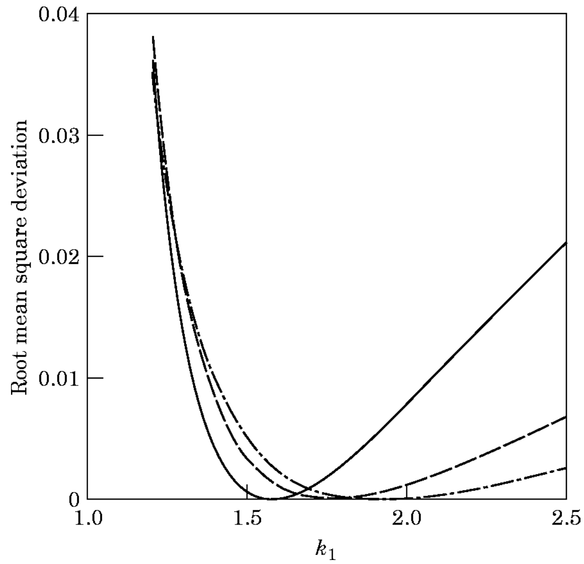

Figure 8. Variation of deviation of distribution function (4) from regression results with k_1. —, $k_2 = 10$; ——, $k_2 = 20$; —·—, $k_2 = 40$. $L_{eq} = 50$ dBA.

reality, at least in air-conditioned landscaped offices [15]. The cumulative distribution for air-conditioned landscape office noise levels can therefore be approximated by

$$F(I) = \exp\{k_2\,[\tanh[k_5\,(\log_e\,(I) + k_1)k_4] - 1]\} \tag{6}$$

though its formulation, unlike that of Kurze [10], is not mathematically rigorous. However, some useful distributions, like the Weibull distribution [19], also suffers from such drawback. A formal derivation of office noise level distribution is left to further investigation.

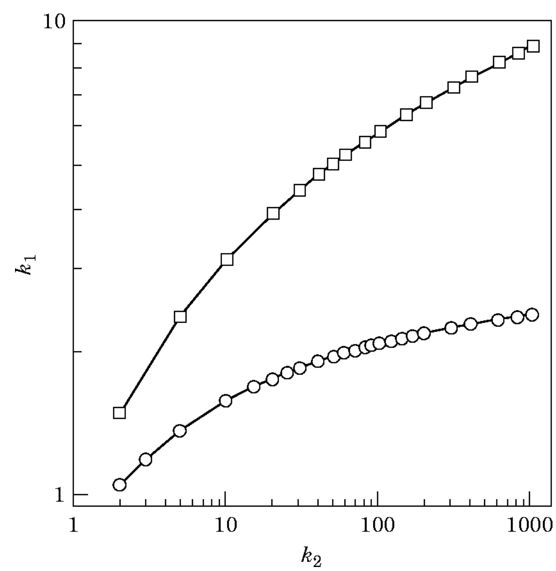

Figure 9. k_1/k_2 pair for minimum deviation of distribution function (4) from regression results. —○—, $L_{eq} = 50$ dBA; —□—, $L_{eq} = 60$ dBA.

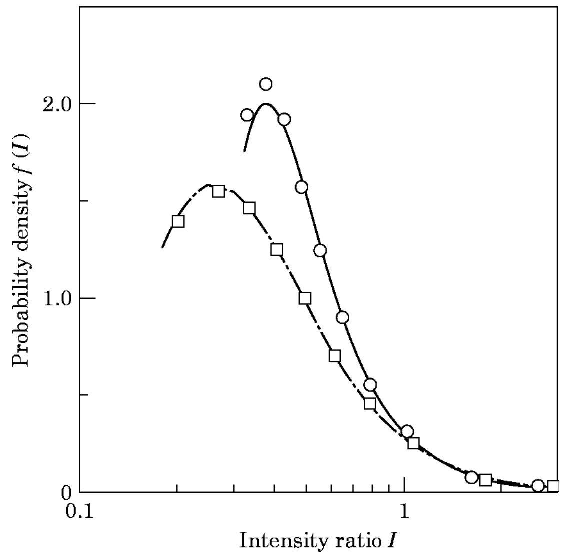

Figure 10. Comparison between probability density function (7) and regression results. ○, Regression results for $L_{eq} = 50$ dBA; □, regression results for $L_{eq} = 60$ dBA; ——, probability density function (7) for $L_{eq} = 50$ dBA; —·—, probability density function (7) for $L_{eq} = 60$ dBA.

In order to complete the testing of the new cumulative distribution function (6), it is worthwhile to compare the probability density distribution function $f(I)$ of $F(I)$ with those obtained from the regression results. $f(I)$ can be obtained by differentiating $F(I)$ with respect to I. Comparison between the predicted and regression results are shown in Figure 10. k_2 is arbitrarily chosen to be 10. For $L_{eq} = 50$ dBA, $k_1 = 1{\cdot}575$, $k_4 = 0{\cdot}617$ and $k_5 = 1{\cdot}681$ while $L_{eq} = 60$ dBA, the corresponding values are 3·129, 1·061 and 0·651 respectively. Though there is a 5% difference in the peak probability density for $L_{eq} = 50$ dBA, $f(I)$ gives good prediction of the most frequently occurring intensity ratio. The matching is very satisfactory, showing that the present proposed function can be used to describe the distribution of office noise level and thus finds application in the design of acoustical environment in air-conditioned landscaped offices. However, though the present proposed office noise distribution function can predict noise distribution at levels lower than L_{90} upon a suitable choice of k_2 (basically a large k_2 will do), it is not presented as the measured data in this range of sound pressure level are not of adequate accuracy.

Results from this section suggest that it is possible to predict the cumulative distribution function and probability density function for noise fluctuations in an air-conditioned landscaped office once L_{eq} is specified. This enables the estimation of skewness, kurtosis and other higher order moments of the noise statistics. It has been found recently by the author that the distribution function (6) is also applicable to noise in a canteen having $L_{eq} > 60$ dBA in general (not shown here). This tends to suggest that this function may have wider application in engineering, at least in the field of acoustics.

5. CONCLUSIONS

In the present study, 1188 noise measurements were carried out in twenty seven air conditioned landscaped offices. The measured data included the equivalent sound pressure level, percentile levels (L_{10}, L_{50} and L_{90}) and noise level cumulative distribution curves. Noise spectra were also recorded.

Results obtained in this study show that linear relationships exist between percentile levels L_N and the equivalent sound pressure level L_{eq} for 45 dBA $< L_{eq} <$ 65 dBA. This suggests the cumulative distribution of air-conditioned landscaped office noise level can be estimated once the equivalent sound pressure level is known. This helps the assessment of the acoustical environment of commercial offices and makes the specification in setting up new office simpler.

The cumulative distribution of office noise found in the present study does not follow the traditional Gaussian, Pearson Type III (Gamma) or Weibull distributions. A new distribution function $F(I)$ which takes the form

$$F(I) = \exp\{k_2 [\tanh [k_5 (\log_e (\mathrm{I}) + K_1)^{k_4}] - 1]\},$$

where I is the intensity ratio, is proposed and its fitting with the measured office noise cumulative distribution is very satisfactory, at least for engineering application. k's are constants which can be determined once L_{eq} is known or specified. The corresponding probability density function also agrees with the average measured noise data. Once this function is found, the estimation of higher order moments of the noise distribution can be done. However, the development of this distribution function is mainly by inspection and, as with the Weibull distribution, is not mathematically rigorous. Formal development, applicability and physical interpretation of this proposed distribution function are left to further investigation. It is also desirable to investigate whether the present distribution function can be applied in other situations.

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