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On noise indices for domestic air conditioners

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Abstract

A survey was carried out in the present study to determine the noise indices which are capable of describing the nuisance caused by exposure to air-conditioner noise inside residential apartments. This survey consisted of a questionnaire, which asked the respondents to rate their feelings of annoyance and loudness on the air-conditioner noise and to give their preference of a change in the noise levels. Physical noise measurements were also carried out. A total of 57 noise spectra and 399 respondents were involved in the survey. Results show that the Zwicker's loudness level and the percentile level of 90% exceedence are the two major indices for air-conditioner noise assessment. Tonality appears not to be a good indicator for such a purpose.

1. Introduction

Air-conditioning is essential for an indoor environment in tropical and sub-tropical climate in which both the outdoor air temperature and humidity well exceed the human comfort limits in summer. However, the use of such technology has brought about the problem of noise. An air-conditioning system of low noise level is especially welcomed as the most important aspect of installing it is to provide a comfortable environment for leisure, relaxation and sleeping.

The noise from the air-conditioning system has attracted the attention of many researchers and engineers during the past few decades because of its importance in the daily life of modern people. Many studies have been devoted to the development of noise descriptors/indices that are able to correlate human annoyance or acceptance in office environment with air-conditioning. Typical examples include the noise criterion (*NC*) of Berenak [1], the noise population level of Keighley [2] and the composite room criterion (*RC*) of Blazier [3], but this list is far from exhaustive. These descriptors/indices are also under regular reviewing and updating (for instance, see Ref. [4]). A

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more recent survey by the first author [5] in the large landscaped air-conditioned offices in Hong Kong reveals that the equivalent sound pressure level is the best index among the commonly adopted ones to correlate human subjective sensation of noisiness at least to the Hong Kong people. A similar survey by Ayr et al. [6] conducted in Italy produced results basically in-line with those of the author [5]. The only major difference is that the percentile level L_{A90} is found by Ayr et al. [6] to be the best index to correlate with human annoyance and the perception of loudness, though L_{Aeq} still correlates well with these feelings in their survey. Results from previous surveys by both Tang [5] and Ayr et al. [6] suggest that the Zwicker loudness level [7] can also be an important index for office noise study. However, the offices surveyed by Ayr et al. [6] were relatively small compared to those of Tang [5].

Although much effort has been made on air-conditioned office noise assessment, only limited results could be found, at least to the knowledge of the authors, in existing literature about the noise created inside residential flats by domestic air conditioners. Bradley [8] conducted a questionnaire survey on the disturbance caused by neighbourhood air conditioners. Socio-economic data were also included. Ko et al. [9] did a similar survey but without the socioeconomics in Hong Kong. However, both of their studies deal with noise created external to a residential unit and were done in the 1980s when the air conditioners were much less popular than they are today. Windows then were expected to be opened, so the ambient background noise level and traffic condition became the important parameters in their studies. Nowadays, air conditioners are installed in every domestic residential flat in many cities within the tropical and sub-tropical climate zones. Windows are all closed when the air-conditioning systems are operated, so that the outdoor noises are usually masked by the air-conditioning noise. A study on the subjective sensations of the residents on the noises produced by their own air conditioners or air-conditioning systems is therefore required.

In the present study, a questionnaire survey has been carried out on air-conditioning noise inside the domestic residential flats in Hong Kong together with physical spectral noise measurements. The performance of the commonly adopted noise indices in relationship with the subjective feelings of the residents toward the noises produced by their own air-conditioning systems is investigated. It is hoped that the best noise index for the assessment of air-conditioning noise inside residential units can be determined.

2. The survey

The questionnaire survey was carried out inside the residential flats in Hong Kong. These flats were occupied by the families of the students of our department or their relatives. They were basically well distributed in all residential districts of Hong Kong. The ages of the buildings vary substantially. The ages of the residents range from 20 to about 60 years. A total of 57 domestic air-conditioner noise spectra and 399 respondents were involved in the present study. The latter included also the family members of the students or their relatives. There was no bias on the gender distribution. All air conditioners involved were in good condition.

The sensation scales adopted in the questionnaire used in the present study are shown in Appendix A. Three scales were adopted and they were all unipolar as in usual practice [6,8,10]. The present loudness and annoyance scales were seven-point unipolar as the one employed by

Bradley [8]. A five-point unipolar preference scale was also adopted in the present study. This scale will enable an evaluation of the subjects' satisfaction with the noises. The respondents were required to express their feelings by ticking the appropriate boxes. Each noise spectrum was rated by at least five respondents.

Spectral measurements were carried out at the locations of the respondents, but in the absence of the respondents, by a RION NA27 sound level analyzer. Statistical parameters, like the L_{Aeq} and the A-weighted percentile levels L_{A10} and L_{A90}, were also recorded. Since the noises were measured with all windows closed, the air conditioners were the major source of noise in the domestic residential flats and the duration of each measurement was usually less than 1 min. The background noise spectra were usually significantly lower than those created by the air conditioners. One-third octave band spectral measurement was adopted so as to allow for an additional analysis of the tonality effect. Noises under the high- and low-fan conditions of the air conditioners were included in the survey. The *NC* values, the Zwicker's loudness levels, the tonality corrections and the composite *RC* data were determined from the measured noise spectra.

3. Noise from domestic air conditioners

Fig. 1 illustrates some noise spectra obtained in the present study. Though they are biased at the low-frequency end, 82% of the air-conditioning noise spectra recorded were balanced according to the composite room criteria adopted by ASHRAE [3]. The remaining 18% show hissy characteristic at or above the 4 kHz octave band. This distribution differs substantially from that

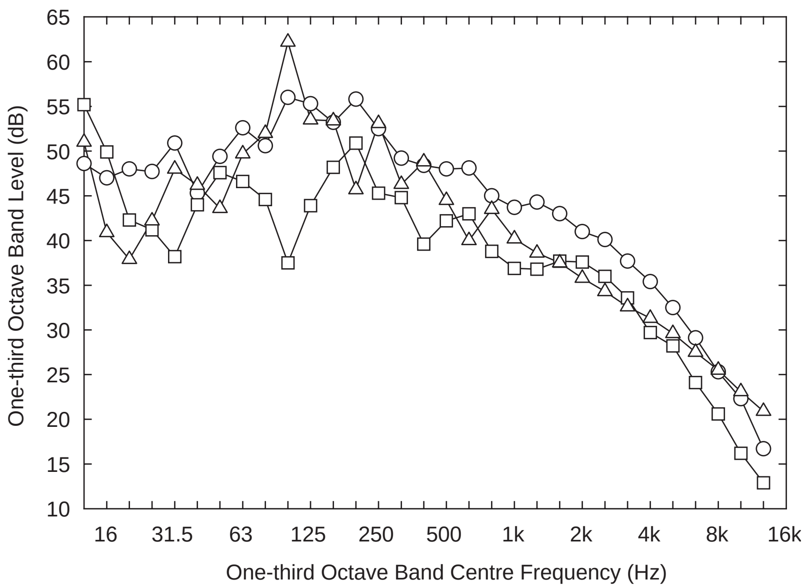

Fig. 1. Typical examples of linear (un-weighted) air conditioner noise spectra. Δ, spectrum of high tonality content (four tonal peaks, correction: 6 dB); ○, a balanced spectrum without tonal peak; □, a hissy spectrum (RC44 H, unbalanced at 4 kHz octave band).

of Ayr et al. [6] which indicates 83% hissy and 17% rumbly noise spectra. Substantial tonality was created by the air conditioners. Tonality and the appropriate correction to the noise level in the later analysis was determined according to the scheme laid down by the local authority with reference to ISO1996 and practices in overseas countries [11]. This scheme is given in Appendix B as an easy reference. Over 70% of the noise spectra contain a certain degree of tonality. Some spectra contain as many as four tonal peaks. The phenomenon of tonality has not been reported so far in similar studies, such as Bradley [8], Ko et al. [9], Ayr et al. [6] and the previous study of the author [5].

Table 1 summarizes the noise indices tested and their ranges in the present study. Unlike the previous study of the first author [5] and that of Ayr et al. [6], the balanced noise criterion [12] was not included here because of its relatively low popularity. The noise rating [13] was also excluded from the present study owing to its anticipated strong correlation with the NC. However, since the air-conditioning noise usually has a rich low-frequency content, the parameter $L_{Ceq}-L_{Aeq}$, which may be able to describe the low-frequency content of the noise in the present study as one does not expect there was much infrasound, was included in the later analysis, even though no rumbly noise spectrum was found in the present study. Also, as tonality was found to be important in the spectral contents of the present air-conditioning noise and its effect has been found to have impact on the human subjective auditory sensation, the effect of tonality was included in the present study in the rating level L_r, which equals the direct arithmetic sum of L_{Aeq} and the associated tonality correction/penalty as in usual practice. One can notice from Table 1 that the range of noise climate (L_{A10}—L_{A90}) here is small. The ranges of the equivalent sound pressure level, the percentile levels, Zwicker's loudness level, RC and NC are comparable to those in the previous studies of the author [5] and Ayr et al. [6]. The loudness level, composite RC and NC values were not considered in the studies of Bradley [8] and Ko et al. [9].

The third column in Table 1 represents the interval of the bin averaging employed in the later statistical analyses on the distributions of noise indices and on the correlation between various indices with the human subjective sensations. Such bin averaging has been used frequently by researchers dealing with environment and human subjective sensations (for instance, see Refs. [5, 14]) and is applicable to indices whose values are continuous. Bin width is not applicable to indices like NC and RC as they are numerical discrete integers.

Table 1
Noise indices and their ranges

Noise index		Range	Bin width
Low frequency content, $L_{Ceq}-L_{Aeq}$	(dB)	7.9–27.7	± 0.5
Equivalent sound pressure level, L_{Aeq}	(dB)	44.1–60.4	± 0.5
Percentile level for 10% exceedence, L_{A10}	(dB)	44.6–61.7	± 0.5
Percentile level for 90% exceedence, L_{A90}	(dB)	43.7–59.7	± 0.5
Rating level, L_r	(dB)	44.1–66.4	± 0.5
Noise climate, $L_{A10}-L_{A90}$	(dB)	0.6–6.2	± 0.5
Zwicker's loudness level, LL_z	(phon)	58.3–75.4	± 0.5
Noise criterion, NC	—	NC 38–57	Not applicable
Composite room criterion, RC	—	RC 40–55	Not applicable

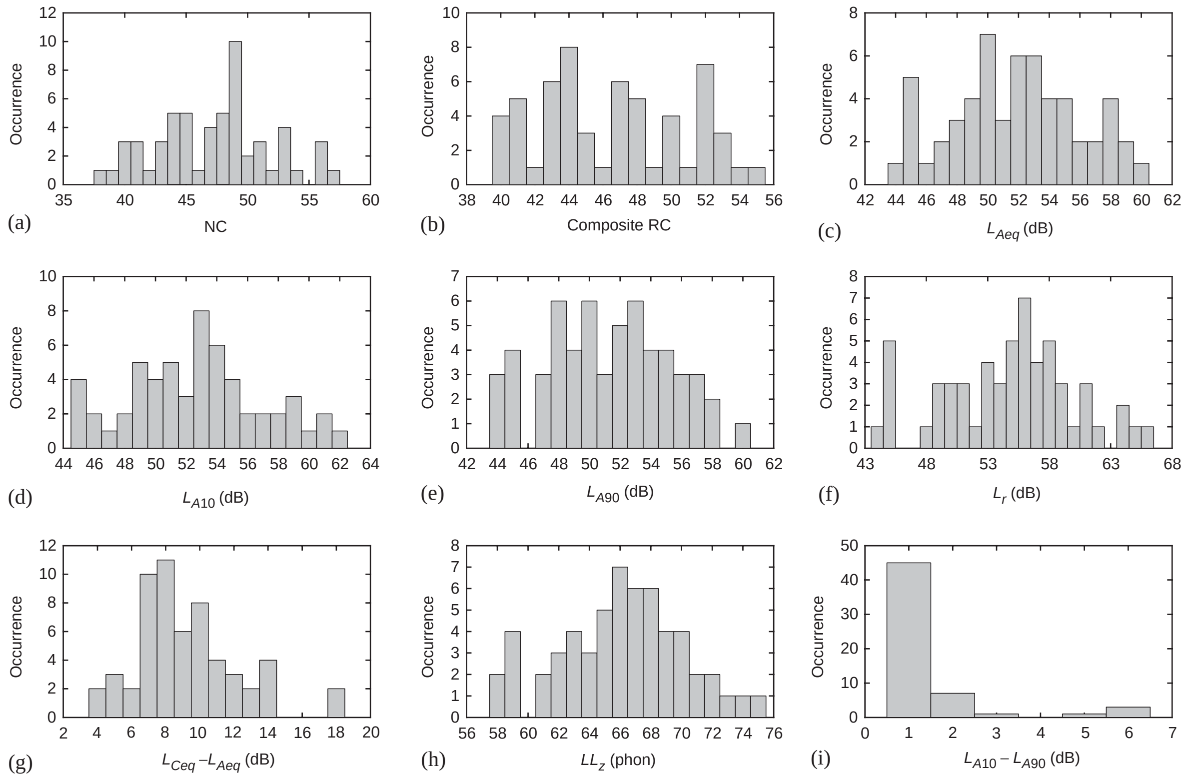

Fig. 2. Distributions of noise indices: (a) NC; (b) RC; (c) L_{Aeq}; (d) L_{A10}; (e) L_{A90}; (f) L_r; (g) L_{Ceq}—L_{Aeq}; (h) LL_z; (i) $L_{A10}-L_{A90}$.

Fig. 2 shows the occurrence statistics/distributions of the noise indices. The occurrence represents the number of counts with a bin width for L_{Aeq}, L_r, $L_{Ceq}-L_{Aeq}$, LL_z, the noise climate and the percentile levels. Those for the NC or RC denote the actual counts at a particular integer value of NC or RC. It can be noted that the L_{Aeq}, L_r, LL_z, L_{A10}, L_{A90}, NC and RC are reasonably well distributed over their ranges (though the NC is a bit concentrated within the range from 48 to 50). The low-frequency content $L_{Ceq}-L_{Aeq}$ is in general less than 18.5 dB. Also, about 79% of the noise climates fall within the range from 0.6 to 1.5 dB as shown in Fig. 2i. This very narrow distribution does not allow a test on the correlation between noise climate and the human auditory sensations. This small noise climate is rather expected as the air conditioners, being the overwhelming sources of noise, were operating steadily during the survey. It is found that there is a strong correlation between the L_{Aeq} and the percentile levels for the air-conditioning noises inside residential flats (Fig. 3). Such phenomena tend to be in line with that observed in large air-conditioned landscaped offices [15]. However, this is out of the scope of the present paper and thus will not be discussed further.

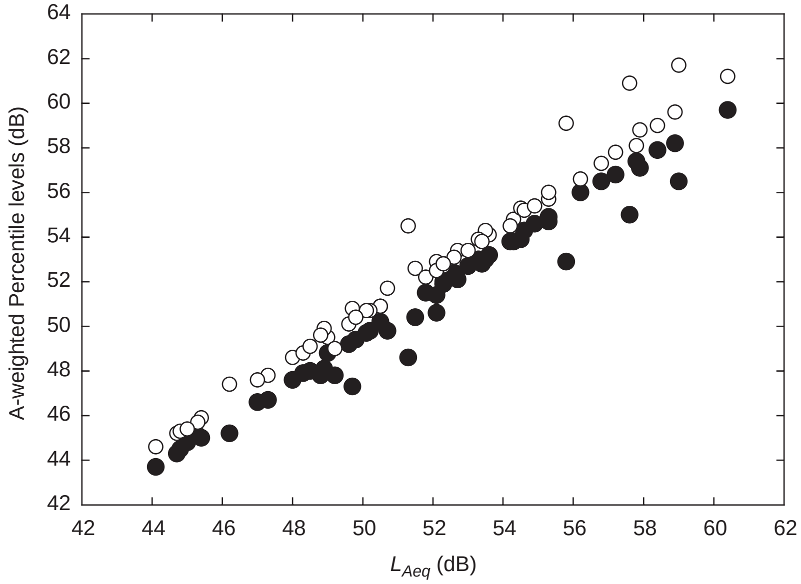

Fig. 3. Relationships between L_{Aeq} and the percentile levels: ○, L_{A10}; ●, L_{A90}.

4. Performance of noise indices

The effectiveness of the noise indices as descriptors of nuisance caused by air-conditioning noise is analyzed by linear regression and the statistical F-test at 95% confidence level with the null hypothesis being that there is no relationship between an index and the human responses (zero slope of the regression line) as in Tang [5]. One index is regarded as better than another index when its correlation coefficient R^2 and the associated ratio $F/F_{1,n-2,0.95}$ are larger than those of the latter. n here denotes the number of data points in the regression analysis. Procedure for the adopted statistical test can be found in standard textbook, such as Bethea and Rhinehart [16]. The null hypothesis will be rejected if the corresponding $F/F_{1,n-2,0.95}$ is greater than 1 in principle.

Fig. 4 illustrates the correlations between various noise indices with the bin-averaged subjective sensation scores. Noise climate is not included in the analysis because of the very concentrated distribution of this index around 0.6–1.5 dB. A summary of the statistical test results is given in Table 2. One can notice that the correlations are in general good, except for $L_{Ceq}-L_{Aeq}$, which even indicates a decrease in the annoyance as the low-frequency content increases (Fig. 4g). However, the observed weak correlation suggests that this conclusion is unreliable. Even weaker correlation is found when the linear overall noise level L_{Leq} is used instead of L_{Ceq} (not shown here). The relative weaker correlation associated with the rating level L_r than with the L_{Aeq} is rather unexpected. This tends to suggest that the tonality, though not a negligible feature in the present study, does not result in additional nuisance in the opinions of the owners of the air conditioners. This may be due to their adaptation to this kind of noise, where a tonal

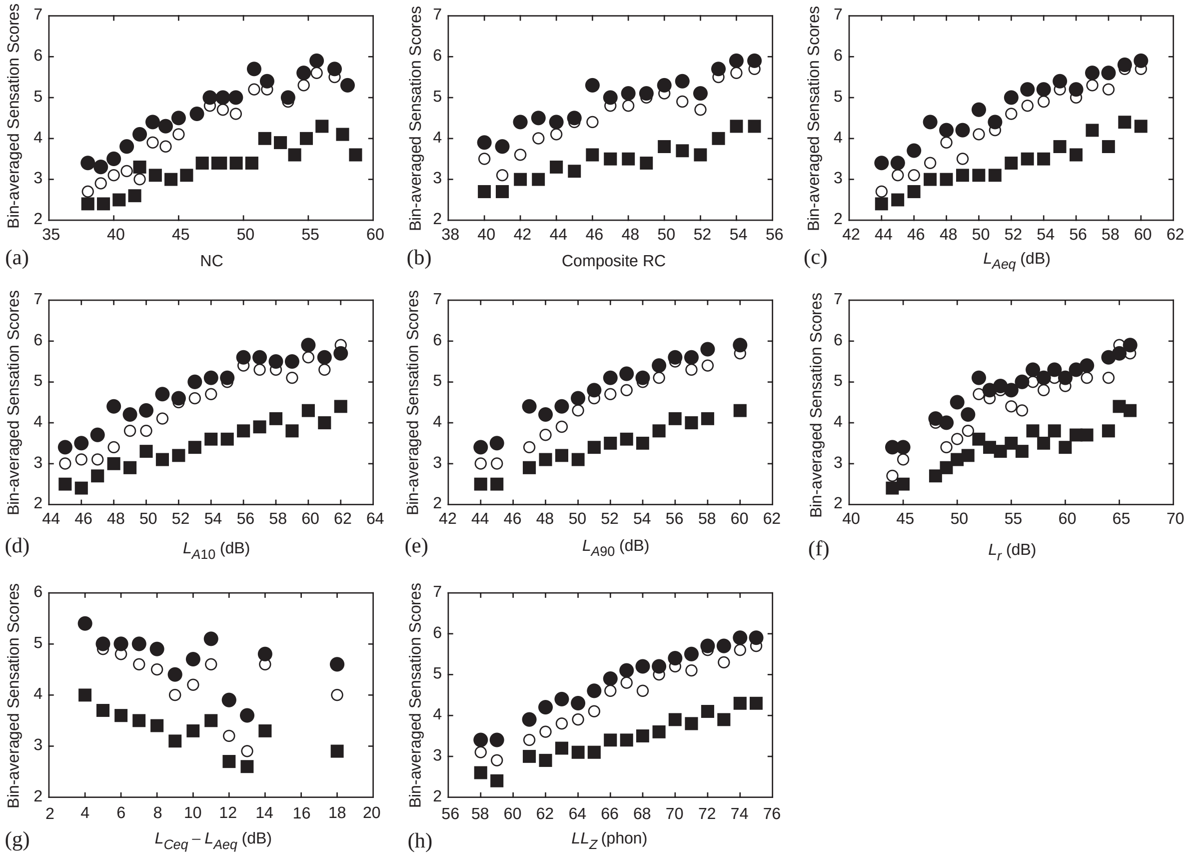

Fig. 4. Correlations between noise indices and subjective, sensation scores (bin-averaged): (a) NC; (b) RC; (c) L_{Aeq}; (d) L_{A10}; (e) L_{A90}; (f) L_r; (g) $L_{Ceq}-L_{Aeq}$; (h) LL_z. ○, Annoyance; ●, loudness; ■, preference.

Table 2
Summary of statistical regression analysis results

Noise index	n	Bin-averaged subjective sensation scores					
		Annoyance		Loudness		Preference	
		R^2	$F/F_{1,n-2,0.95}$	R^2	$F/F_{1,n-2,0.95}$	R^2	$F/F_{1,n-2,0.95}$
$L_{Ceq}-L_{Aeq}$	12	0.388	1.3	0.312	0.9	0.588	2.9
L_{Aeq}	17	0.961	80.6	0.940	60.5	0.947	59.6
L_{A10}	18	0.938	54.3	0.923	42.9	0.941	56.5
L_{A90}	15	0.961	69.1	0.948	50.4	0.968	82.9
L_r	20	0.866	26.9	0.901	37.5	0.852	23.8
LL_z	17	0.964	87.5	0.973	118.3	0.954	68.6
NC	19	0.900	34.5	0.861	23.6	0.801	15.4
RC	16	0.900	27.3	0.889	24.3	0.901	27.6

characteristic is commonly expected. Among the indices involved in the present study, the loudness level LL_z [7], the L_{Aeq} and the L_{A90} appear to be the better ones so far as annoyance is concerned. The LL_z comes first. The performance of the latter two indices is comparable, but that of L_{A10} is a bit worse.

The observation in the previous paragraph is basically consistent with the conclusions of Tang [5] and also Ayr et al. [6] regarding the major noise descriptors, even though their results tend to suggest that the LL_z is less effective than the L_{Aeq} and L_{A90} in correlating with human annoyance sensations. However, one can observe that the noise in the survey of Tang [5], which was recorded in large offices, contains significant contributions from various sources, such as human activities and other office operations. The sizes of the offices in the survey of Ayr et al. [6] appear much smaller with occupancy less than 10 per office. Though the ranges of noise climate and L_{Aeq} in these two studies are very similar, the noise in Ayr et al. [6] seems to be more steady as there is a higher proportion of noise climate which is less than 8 (more positively skewed distribution). The noises in the present study are even more steady as they were obtained under the steady operation of the air conditioners with windows closed. The average occupancy is the smallest when compared to those of Tang [5] and Ayr et al. [6]. One can then observe a trend of the relative importance of the noise indices. In Tang [5], the performance of L_{Aeq}, L_{A90} and L_{A10} in correlating with human annoyance scores is better than that of the LL_z and is far better than that of *NC* and *RC*. As the noise becomes more steady, the importance of LL_z and the *NC*, especially the former, is improved. The LL_z slightly takes over the L_{A90} and the L_{Aeq} in the present study where the noise is steady. The performance of *NC* and *RC* in describing human annoyance is improved substantially. Spectral content becomes more important to human sensations of annoyance and loudness as the noise becomes steady, but the tonality does not lead to increased annoyance.

In Fig. 4 and Table 2 show also the statistical regression analysis results concerning the annoyance, loudness and preference scores. As far as loudness of air-conditioning noise is concerned, the Zwicker's loudness level correlates the best with the loudness scores. The second best being the L_{A90} and the L_{Aeq}. This is slightly different from the result of Ayr et al. [6] which shows the L_{Aeq} and the percentile levels correlate better with the loudness score. Loudness scale was not included in the survey of Tang [5]. When preference is concerned, the L_{A90}, which can be considered as the average background noise level for steady noise, performs the best, followed by the loudness level LL_z. This suggests that the respondents base their acceptance of air-conditioning noise on the A-weighted background noise level more than on the loudness and annoyance. Since the preference score also reflects the degree of satisfaction or dissatisfaction with the noises, it may be more reliable than the previous two scales in describing human reaction to noise as suggested by Job et al. [17]. However, further investigation is required to clarify this issue.

There is a strong correlation between the annoyance and the loudness scores ($R^2 = 0.76$, $F/F_{1,n-2,0.95} = 324.9$), but that between the annoyance and the preference scores is relatively poor ($R^2 = 0.03, F/F_{1,n-2,0.95} = 3.1$). This may be due to the fact that some people might be able to tolerate to some extent a noise which they consider annoying or noisy if they have to pay for a change. Fig. 5 shows the plots of bin-averaged loudness and preference scores against the annoyance scores. It is noted that the annoyance and loudness scales actually merge at the high ends of the scales. The increasing difference between these two scores towards the low end

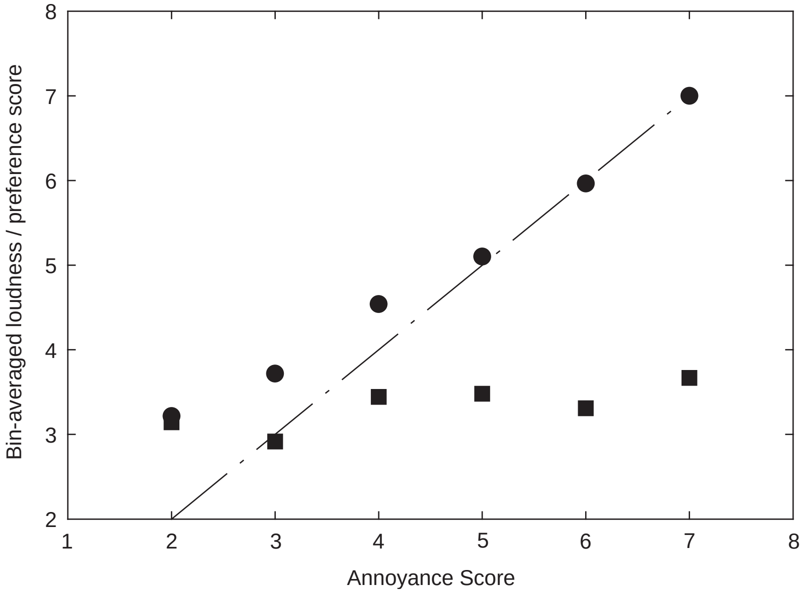

Fig. 5. Correlations between the three adopted scales: ●, between annoyance and loudness scores; ■, between annoyance and preference scores; —·—, line of equal abscissa and ordinate.

suggests that people tend to accept a certain degree of loudness before the noise becomes annoying to them.

5. Conclusions

In the present investigation, the subjective feelings of residents to the indoor noises produced by their own air conditioners were sought through a questionnaire containing the annoyance, loudness and preference scales. Physical measurements of noises under steady operation of the air conditioners were carried out. The main objective is to determine the best indices for describing the nuisance caused by domestic air conditioners.

It is observed that the noises dealt with in the present study are much more steady than those reported in similar studies. About 80% of the noise spectra were balanced, but 70% of them contained a certain degree of tonality. However, it is observed that the respondents do not tend to have strong feeling about the tonal characteristic of the present air-conditioner noises, or they may have adapted to this kind of noise. In general, the equivalent sound pressure level, the A-weighted percentile levels for 10% and 90% exceedence, the Zwicker's loudness level, the noise criterion and the composite room criterion correlate well with the sensations of annoyance and loudness of the respondents and their preference. The Zwicker's loudness level appears to be the best one among those noise indices included in the present study to correlate with human annoyance and perception of loudness. The preference of the people appears to correlate more with the A-weighted percentile level for 90% exceedence.

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Appendix A

As stated in the text, this appendix provides the three subjective sensation scales in the questionnaire adopted in the present study.

Not Annoyed			Medium			Extremely Annoyed
1	2	3	4	5	6	7

Annoyance Scale

Not Loud			Medium			Extremely Loud
1	2	3	4	5	6	7

Loudness Scale

Not Varied				Much Less Loud
1	2	3	4	5

Preference Scale

Appendix B. Tonality correction scheme adopted by local authority (an extraction from Ref. [11])

A correction for tonality shall be applied if, between 31.5 and 16 Hz, any one-third octave band or any pair of adjacent one-third octave bands of the A-weighted spectrum of the noise under investigation satisfies all of the following conditions:

(a) the level of the one-third octave band under consideration, or, in the case of a pair of bands, the level of the highest band in that pair, is not more than 15.0 dB below the level of the highest one-third octave band;
(b) the level of the one-third octave band under consideration, or, in the case of a pair of bands, the arithmetic average of the levels of the two bands, is more than 1.0 dB higher than the level of each of the adjacent bands on either side of the band or pair of bands under consideration; and

(c) the level difference, known as the tonality factor, f_{tone}, between the level of the one-third octave band under consideration, or, in the case of a pair of bands, the arithmetic average of the levels of the two bands, and the arithmetic average of the levels of the adjacent bands on either side of the band or pair of bands under consideration is 3.0 dB or more.

Where the noise under investigation is assessed to have a tonal characteristic with a tonality factor, f_{tone}, the correction, c_{tone}, to the measured noise level shall be as shown in the following table :

F_{tone} (dB)	Tonality correction/penalty, c_{tone} (dB)	
	In cases where the frequency of any band under consideration is below 250 Hz	In cases where the frequency of any band under consideration is higher than or equal to 250 Hz
Greater than or equal to 3 and less than 6	0	3
Greater than or equal to 6 and less than 9	3	6
Greater than or equal to 9	6	6

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