SOUND QUALITY EVALUATION OF AIR CONDITIONER NOISE

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ABSTRACT

The aim of this paper is to clarify the characteristics of air conditioning noise and determine the factor that is most influential on the subjective level of user annoyance caused by this noise. The A-weighted equivalent continuous sound pressure level (\(L_{Aeq}\)) and factors extracted from the autocorrelation function (ACF) were analyzed. Subjective user annoyance was evaluated using a paired comparison method. Multiple regression analyses were performed using a linear combination of \(L_{Aeq}\), the ACF factors, and their standard deviations (SDs). The results indicated that the noise characteristics caused by each air conditioner and each operating level are determined by \(L_{Aeq}\) and by the width of the first decay of the ACF, \(W_{\phi(0)}\), which corresponds to the spectral centroid. The multiple regression analyses indicated that the total subjective user annoyance caused by air conditioner noise can be predicted using the delay time and the amplitude of the first maximum peak of the ACF (\(\tau_1\) and \(\phi_1\)) and the SD of \(\phi_1\). Annoyance was found to increase with decreasing \(\tau_1\) and \(\phi_1\), and with an increasing SD of \(\phi_1\), and showed that noise components with higher pitches, weaker pitch strength, and larger pitch strength variations cause greater levels of user annoyance.

Keywords: Air conditioner noise; Autocorrelation function; Pitch; Pitch strength; Spectral centroid

1. INTRODUCTION

Large electrical appliances such as air conditioners, refrigerators, vacuum cleaners, and washing machines are regarded as major noise sources in indoor environments. Air conditioners are widely used in classrooms, offices, and residences for long periods, and thus considerable efforts have been made to reduce the sound levels of these devices during operation. As results, the sound levels of air conditioners are now comparatively low (Ayr et al. 2001; Tang and Wong 2004). However, people may still be made to feel uncomfortable by certain aspects of the sound quality, even when the actual sound level of the air conditioners is low (Kitamura et al. 2002). Therefore, both the sound levels and the sound quality of an air conditioner are important for the user’s acoustic comfort.

To evaluate air conditioning noise, many researchers have developed methods that can correlate human annoyance with the noise within a building environment. Noise criterion (NC) curves were proposed to evaluate indoor noise, the noise from air conditioning equipment, and other noise factors (Beranek 1956). The frequency range of NC curves is from 63 to 8000 Hz. Preferred noise criterion (PNC) curves are modified versions of the original NC curves (Beranek 1971). The PNC curve evaluates lower frequencies than the NC curve, i.e., the PNC analyzes the 31.5 Hz band, while the NC does not analyze that band. Noise rating (NR) curves are based on similar assumptions to those of the PNC. The NC and PNC curves are used in the USA, while the NR curve is used in Europe.
Balanced noise criterion (NCB) curves are a further modified version of the NC and PNC curves that consider the balance between low and high frequency noises, such as rumbling and hissing noises (Beranek 1989). Room criteria (RC) curves were developed and applied differently to the NC and PNC curves (Blazier 1981). RC curves have a constant slope in the frequency range from 16 to 4000 Hz. RC Mark II curves are revised versions of the original RC curves and have lower values than the corresponding RC curves at 16 Hz (Blazier 1997, 2000). Room noise criterion (RNC) curves were proposed to allow technical compromises to be reached between the NC, NCB, and RC curves (Shomer 2000; Shomer and Bradley 2000). RNC curves involve evaluations of the temporal variations in low frequency sound.

Large numbers of noise indices have been proposed by numerous researchers for evaluating environmental noise. The A-weighted equivalent sound pressure level (SPL), denoted by $L_{Aeq}$, is the most widely used of the proposed indices. This index accounts for both the magnitude of a noise and the sensitivity at different frequencies, is simple to measure, and correlates well with many psychological responses to noise, such as annoyance (Namba and Kuwano 1984; Kuwano et al.1989; Ayr et al. 2003). The A-weighted statistical levels (denoted by $L_{A90}$, $L_{A10}$, and $L_{A5}$) are important because they account for the noise’s time dependence. $L_{A90}$ represents the background noise, while $L_{A10}$ and $L_{A5}$ represent the noise peaks, and the difference $L_{A10} - L_{A90}$ represents the noise fluctuations (Kryter 1970). The noise pollution level (LNP) was defined as the sum of $L_{Aeq}$ and the difference $L_{A10} - L_{A90}$, and was introduced to describe the degree of annoyance that is caused by fluctuating noise (Robinson 1971). The office noise index (ONI) is based on the same principle as the LNP, with the difference that $L_{A90}$ replaces $L_{Aeq}$ and the difference factor (Hay and Kemp 1972). A wide-ranging acoustic environment survey recently proved that $L_{Aeq}$ is the best index to use for assessment of the subjective ratings of annoyance, loudness and dissatisfaction, when compared with several other indices, including NC, PNC, NCB, NR, RC, RNC, $L_{A90}$, $L_{A10}$, $L_{A5}$, LNP, and ONI (Ayr et al. 2003).

However, these indices are determined on the basis of both the SPL, i.e., the quantitative aspects of the noise, and the frequency characteristics of the noise. In noise evaluation, it is also necessary to consider the qualitative aspects of a noise because people may be annoyed by certain aspects of sound quality even when the SPL of the noise is quite low, e.g., less than 40 dBA (Kitamura et al. 2002). These aspects can be formulated using factors that are calculated based on the autocorrelation function (ACF) and the interaural cross-correlation function (IACF) of the noise arriving at the two entrances to human ears. This study deals with the ACF factors for evaluation of the noise characteristics or sound quality of air conditioning noise, although a number of basic psychoacoustic indices such as loudness, sharpness, roughness, and fluctuation strength have also been widely used as sound quality indices (Zwicker and Fastl 1999). One rationale for this approach is that the perception of the quality of most sounds is based on information that is embedded in the timing of the spikes in the sound, i.e., the temporal correlation representations arise from spike timing patterns in the auditory nerve, and this is reflected in the ACF of the sound (Cariani and B. Delgutte 1996a; 1996b). Another rationale is that the ACF factors describe the basic temporal sensations, such as pitch, loudness, or timbre (Ando and Cariani 2009). In addition, the subjective annoyance caused by various noise sources including road traffic (Fujii et al. 2002), trains (Soeta and Shimokura 2013a; 2013b), floor impacts (Jeon and Sato 2008), and refrigerators (Sato et al. 2007) can be predicted using the ACF factors. The aim of this study is to clarify air conditioning noise characteristics using the ACF factors and thus determine the factor that is the most dominant in terms of the subjective annoyance caused by this noise.
2. METHODS

2.1 Analysis of air conditioning noise

Air conditioning noise generated by two cassette-type (CT1 and CT2) and five split-type air conditioners (ST1, ST2, ST3, ST4 and ST5), and one central air conditioning system (CA), were measured at two or three operational levels (high, middle, or low) using an omnidirectional microphone. The microphone was placed just below the cassette-type air conditioners, in front of the split-type air conditioners, and at the position where the noise from the central air conditioning system was most clearly heard. Although no wind screen was used, the microphone was set such that it was not placed directly in the path of the air currents. For all measurements, the noise was recorded via an analog-to-digital/digital-to-analog (AD/DA) converter at a sampling rate of 44.1 kHz and with a sampling resolution of 24 bits.

The ACF factors of noise have been proposed previously for sound quality evaluation (Ando and Cariani 2009; Soeta and Ando 2015). To calculate the ACF factors, the normalized ACF of the signals recorded from the microphones, \( p(t) \), as a function of the running step, \( s \), is defined by

\[
\phi(\tau) = \phi(\tau; s, T) = \frac{\Phi(\tau; s, T)}{\sqrt{\Phi(0; s, T) \Phi(0; s + \tau, T)}},
\]

where

\[
\Phi(\tau; s, T) = \frac{1}{2T} \int_{-T}^{T} p'(t) p'(t + \tau) dt.
\]

Here, \( 2T \) is the integration interval and \( p'(t) = p(t)^* s(t) \), where \( s(t) \) is the ear sensitivity. \( p(t) \) is the signal that was measured using the omnidirectional microphone in this study. \( s(t) \) represents the impulse response of an A-weighted network, including the transfer functions of the human outer and middle ear, for convenience (Ando and Cariani 2009; Soeta and Ando 2015). Normalization of the ACF is carried out using the geometric mean of the energy at \( s \) and the energy at \( s + \tau \).

The 1/3 octave-band power levels and \( L_{\text{Aeq}} \) were both determined from the 1/3 octave-band filtered and A-weighted \( p(t) \) signal as a function of \( s \). \( L_{\text{Aeq}} \) is then calculated using

\[
L_{\text{Aeq}}(s, T) = 10 \log \Phi(0; s, T).
\]

This means that the ACF includes \( L_{\text{Aeq}} \) as one of its factors. \( L_{\text{Aeq}} \) was calibrated using a sound calibrator (Type 4231, B&K).

The other ACF factors are calculated from the normalize ACF (Ando and Cariani 2009; Soeta and Ando 2015). \( \tau_1 \) and \( \phi_1 \), are defined as the time delay and the amplitude of the first maximum peak. \( \tau_1 \) and \( \phi_1 \) are related to the perceived pitch and the pitch strength of the complex sounds, respectively (Yost 1996; Ando and Cariani 2009). The other ACF factor, \( W_{\phi(0)} \), is defined using the delay time interval at a normalized ACF value of 0.5, and it represents the width of the first decay. \( W_{\phi(0)} \) is equivalent to the spectral centroid.

Psychoacoustic factors including loudness, sharpness, roughness, and fluctuation strength have been used for sound quality evaluation (Zwicker and Fastl 1999). Loudness is the psychological counterpart of the physical strength of a sound, and considers the transfer function of the outer and middle ear, the frequency and the temporal masking effects. In this study, the non-stationary time-varying loudness was considered (Zwicker 1997). Sharpness is a measure of the high frequency content of sound, where a higher proportion of high frequency components indicates a sharper sound. The sharpness of a sound can be calculated via addition of a weighting function to its specific loudness spectrum (Zwicker and Fastl 1999). Roughness quantifies the subjective perception of the rapid (15–300 Hz) amplitude modulation of a sound. Roughness is generally calculated using the
time-varying loudness multi-spectrum. For this study, a modified version of the roughness calculation was considered (Daniel and Weber 1997). The fluctuation strength is similar in principle to the roughness, but it quantifies the subjective perception of the slower (at frequencies up to 20 Hz) amplitude modulation of the sound. The sensation of the fluctuation strength persists up to 20 Hz before the roughness takes over for the higher frequencies. The fluctuation strength is also calculated using the time-varying non-stationary loudness multi-spectrum (Zwicker and Fastl 1999).

We calculated the 1/3 octave-band noise levels, $L_{Aeq}$, $\tau_1$, $\phi_1$, and $W_{\phi(0)}$ as a function of time to evaluate the noise both quantitatively and qualitatively. The integration interval was $2T = 0.5$ s and the running step was $s = 0.1$ s in all calculations. We also calculated the loudness, the sharpness, the roughness, and the fluctuation strength. The temporal windows used for the analysis was $0.5$ s. The analyses were conducted using a Matlab-based analysis program.

2.2 Subjective annoyance tests

Subjective annoyance caused by air conditioner noise was evaluated to clarify the effects of the ACF factors on annoyance. Fourteen participants with normal hearing, no history of neurological diseases, and an age range of between 20 and 40 years (median age of 22.5 years), took part in the experiments. Informed consent was obtained from each participant after the nature of the study was explained. The study was approved by the ethics committee of the National Institute of Advanced Industrial Science and Technology (AIST), of Japan.

Eight stimuli were detected from the measured air conditioning noise. These stimuli were CT1, CT2, ST1, ST4, ST5 and CA at the low level and ST2 and ST3 at the high level. The duration of each stimulus was 2.5 s. The stimuli were presented binaurally through headphones (HD650, Sennheiser). The monaural signal measured by the omnidirectional microphone was presented binaurally. The participants sat in a comfortable thermal environment in a soundproof room to hear the auditory stimuli. All stimuli were presented at the same $L_{Aeq}$ as the actual measured stimuli. $L_{Aeq}$ was verified using a dummy head microphone (KU100, Neumann) and a sound calibrator (Type 4231, B&K).

Scheffe’s paired comparison tests (Scheffe 1952) were performed for all combinations of pairs (i.e., 28 pairs ($N(N-1)/2, N = 8$)) of stimuli, by interchanging the order in which the stimuli in each pair were presented in each session and by presenting the pairs in random order. The rise and fall times were 100 ms, and the silent interval between stimuli was 1.0 s. After the presentation of each pair of stimuli, the participants were required to compare the two stimuli in each case based on five grades by considering the differences between the two stimuli. Four sessions were conducted for each participant. The approximate duration of a single session was ten minutes, and sessions were carried out in pairs consecutively. The interval between the first and second sessions was five to ten minutes.

The averaged scale values of annoyance according to each participant were calculated based on the modified Scheffe’s method (Sato 1985). Analysis of variance (ANOVA) was then conducted on the results of the paired comparison experiments. To calculate the effects of each objective factor on participant annoyance, multiple regression analyses were conducted using a linear combination of $L_{Aeq}$, the ACF factors and their standard deviations (SDs) as predictive variables by stepwise procedures in model 1. The predictive variables were the loudness, sharpness, roughness, fluctuation strength, and their SDs in model 2. The analyses were carried out using SPSS statistical analysis software (SPSS version 22.0, IBM).
3. RESULTS AND DISCUSSION

3.1 Analysis of air conditioning noise

Figure 1. Measured SPL values as a function of the 1/3 octave-band center frequency for each air conditioning noise at each operational level
Figure 1 shows the averaged 1/3 octave band levels for each air conditioning noise. Basically, the noise levels decreased as the frequency increased, and this is consistent with previous findings (Kuwano et al. 1989; Tang 1997; Ayr et al. 2001; Jeon et al. 2001; Tang and Wong 2004). The frequency characteristics of the noise did not show larger differences between the operational levels (low, middle, and high).

Figure 2 shows the ACF factors ($L_{Aeq}$, $\tau_1$, $\phi_1$, and $W_{\phi(0)}$) of the noise generated by each air conditioner. The $L_{Aeq}$ values were between 40 and 60 dBA, which was quite low when compared with outdoor noise sources such as road traffic, trains, and airplanes (Fujii et al. 2001; 2002; Soeta and Shimokura 2013a; 2013b). The $\tau_1$ values showed large differences among the air conditioners. Most $\phi_1$ values were less than 0.2, which is lower than the typical values that were measured in train stations (Soeta and Shimokura 2013a), in train cars (Soeta and Shimokura 2013b), on floor impact (Jeon and Sato 2008), from refrigerators (Sato et al. 2007), and in airplanes (Fujii et al. 2001), which indicates that these noises generate no clear pitch. The $\tau_1$ and $\phi_1$ values varied considerably with the differences in the operating modes at CT2, ST3, and ST4. In these cases, the $\tau_1$ and $\phi_1$ values have a negative correlation ($r = -0.90$), suggesting that there are some noise sources, and noise with a low pitch has a relatively strong pitch. In addition, the dominant noise source can be different for the different operating modes at CT2, ST3, and ST4. Most $W_{\phi(0)}$ values were higher than 0.4, which is higher than the levels measured in train stations (Soeta and Shimokura 2013a) and in train cars (Soeta and Shimokura 2013b). This suggests that the air conditioning noise includes lower frequency components. Roughly speaking, the $W_{\phi(0)}$ values decreased with increasing operational level, indicating that the high frequency components increase as the operational level increases.

Figure 2. Mean values of (a) $L_{Aeq}$, (b) $\tau_1$, (c) $\phi_1$, and (d) $W_{\phi(0)}$ ($\pm$ standard deviations) of noises generated by each air conditioner at each operational level.
Figure 3 shows the loudness, sharpness, roughness, and fluctuation strength of the noise that is generated by each air conditioner. The loudness values increased with increasing operational level. The sharpness values were all approximately 1.0. The effects of the operational level were not clear. The roughness values increased with increasing operational level, except in the case of ST2 and ST5. The fluctuation strength values were between 0.5 and 1.0. The fluctuation strength values also increased slightly with increasing operational level, except in the case of ST2 and ST5.

Figure 3. Mean values of (a) loudness, (b) sharpness, (c) roughness, and (d) fluctuation strength (± standard deviations) of noises generated by each air conditioner at each operational level.

Figure 4. Scale values of annoyance for the eight air conditioning noises. Each individual symbol indicates an individual participant.
3.2 Subjective annoyance tests

ANOVA for the scale value of the annoyance revealed that the primary effect (i.e., the differences between the stimuli) was statistically significant \((p < 0.001)\). There was a statistically significant interaction between the primary effect and the participant. However, there were no significant effects caused by the combination of the stimuli. The averaged scale values of annoyance for the eight air conditioning sets are shown in Fig. 4. The relationships between the averaged scale value of the annoyance and each factor are presented in Fig. 5. Annoyance was found to increase with increasing \(L_{\text{Aeq}}\), loudness, roughness, and fluctuation strength, and with decreasing \(\tau_1\), suggesting that components that were louder, were subject to greater amplitude modulation, or were at a higher pitch caused greater levels of annoyance.

A multiple linear regression analysis was performed with the scale values of annoyance for all participants as the outcome variable. The final model for model 1 indicated that \(\tau_1\), \(\phi_1\), and the SD of \(\phi_1\) were the significant factors:

\[
SV_{\text{annoyance}} \approx a_1 \cdot \tau_1 + a_2 \cdot \phi_1 + a_3 \cdot \text{SD}_{\phi_1} + c.
\]

The model was statistically significant \((p < 0.001)\), and the modified determination coefficient was 0.87. The standardized partial regression coefficients of the variables \(a_1\), \(a_2\), and \(a_3\) in Eq. (4) were \(-1.17\), \(-0.61\), and 0.20, respectively. The negative coefficients for \(\tau_1\) and \(\phi_1\) indicate that the higher pitch components and weaker pitch strength of the noise cause greater annoyance. A previous study on annoyance cause by floor impact sound indicated that the SD of \(\phi_1\) is one of the significant factors for annoyance evaluation (Jeon and Sato 2008). This is consistent with the present findings.

The final model for model 2 indicated that the loudness, the SD of the roughness, and the roughness were the significant factors:

\[
SV_{\text{annoyance}} \approx b_1 \cdot \text{loudness} + b_2 \cdot \text{SD}_{\text{roughness}} + b_3 \cdot \text{roughness} + d.
\]

The model was statistically significant \((p < 0.001)\) and the modified determination coefficient was 0.87. The standardized partial regression coefficients of the variable \(b_1\), \(b_2\), and \(b_3\) in Eq. (5) were 0.50, 0.35, and 0.12, respectively.

4. CONCLUSIONS

We analyzed the characteristics of air conditioning noise to determine the factor that is most influential on subjective annoyance caused by this noise. The results indicated that the \(L_{\text{Aeq}}\) and \(W_{\phi(0)}\) values clearly show the differences in the noise characteristics for different air conditioners and operational levels. The values of \(\tau_1\) and \(\phi_1\) were significantly influential factors in the subjective annoyance caused by air conditioner noise.

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Figure 5. Relationships between the scale value of annoyance and (a) $L_{Aeq}$, (b) $\tau_1$, (c) $\phi_1$, (d) $W_{\phi(0)}$, (e) loudness, (f) sharpness, (g) roughness, or (h) fluctuation strength. Error bars indicate standard deviations. Asterisks represent the level of significance, i.e., ** $p < 0.01$, * $p < 0.05$. 
6. REFERENCES