ACF 및 심리음향 파라미터에 의한 냉장고 소음의 Sound Quality 평가

Sound Quality Characteristics of Refrigerator Noise in relation to Autocorrelation Function and Psychoacoustical Parameters

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ABSTRACT

This study investigates objective and subjective evaluations of refrigerator noise. To describe the fluctuations like a click, a rapid increase of sound level, a change of pitch, a transition into the stationary and ending phase, the psychoacoustical and autocorrelation function (ACF) parameters have been employed. First, subjective evaluation of the noisiness of 24 kinds of refrigerators was conducted. Then, the relationship between objective measures of the refrigerator noise on perceived noisiness was examined with multiple regression analyses. Sound Quality Indices using the psychoacoustical and ACF parameters were also developed. The important psychoacoustical parameters for evaluating noisiness are loudness and roughness of stationary phase. The relationship between the noisiness and the ACF parameters shows that sound energy $\Phi(0)$ and its fluctuations are important. Also, refrigerator sounds that had a fluctuation of pitch were rated as more annoying. The fluctuation of pitch is expressed by τ_1 and ϕ_1 defined by the delay time and the amplitude of the first peak of the ACF.

1. Introduction

The number of complaints about noise in living environments is rapidly increasing, including concerns about noise from household electric appliances. Refrigerators, unlike other home appliances, operate all day. Refrigerator owners are sensitive to the noise refrigerators generate, and it has been reported that noise level is among the most important consumer criteria when buying household appliances[1]. It is necessary to reduce the noise levels of refrigerators. Compressors and fans are the primary sources of refrigerator noise. Structural improvements can reduce the level of noise produced by these parts. For example, the application of a flexible joint on the back cover of a refrigerator has been shown to reduce its sound pressure level by 2 dB[2].

Despite the continuous reduction of refrigerator noise levels, complaints and indications of noise discomfort persist. Therefore, it is necessary to consider sound quality in studying this issue. In terms of psychoacoustics, noise from home appliances is not only influenced by SPL, but also by time of day, duration of noise, background noise, and frequency characteristics. Also, studies on the relationship between objective measurements of and subjective responses to refrigerator noise should be conducted.

The psychoacoustical parameters were designed to quantify a listener's perception and evaluation of sound quality[3]. These parameters are used as a sound quality index for noises. Loudness considers both frequency and temporal masking. The high-frequency components of a sound determine its perceived sharpness, and the sharpness of sound increases annoyance. Roughness and fluctuation strength describe the fluctuation of the signal. Target modulation frequencies of roughness and fluctuation strength are around 70 and 4 Hz, respectively. Our previous study also investigated the Sound Quality Index of the stationary part of refrigerator noise[4], which showed that the psychoacoustical parameters that significantly influenced evaluations of refrigerator noises were loudness and roughness.

Refrigerator noise, especially when operation begins, contains temporal fluctuations in sounds, such as a click, a rapid increase in volume, and a change in pitch. The ACF parameters may also describe noises related to sensory perception like loudness, pitch, timbre, and duration. It has been found that the perceived pitch and strength (i.e., tonality) of complex sounds are extracted from the maximum peak in the ACF[5]. The time delay of the maximum peaks of an ACF for a given sound source was used as a significant parameter for predicting the pitch in the pitch-matching study. The loudness and annoyance of narrowband noise are related to the decay rate of the normalized ACF envelope, which describes the degree of persistence/randomness of a sound signal[6,7]. These factors have been utilized to describe the acoustic properties of aircraft, trains, traffic, drainage, and floor impact sounds[8-14].

The purpose of the present study is to investigate the effects of psychoacoustical and ACF parameters on the subjective evaluation of noise generated by the starting

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phase as well as the stationary phase of refrigerator operation. First, acoustical characteristics of the sounds were clarified using psychoacoustical and ACF parameters. Subjective tests were conducted to obtain a subjective rating score. The relationships between noisiness and objective measures were examined by multiple regression analyses and SQ Indices. Finally, the ending phase of refrigerator operation was characterized by psychoacoustical and ACF parameters.

2. Noisiness of refrigerator sounds in terms of psychoacoustical and ACF parameters

2.1 Subjective evaluation test

In total, 24 refrigerator sounds of 6 manufacturers from 2 countries (Korea and USA) were used for the test. These refrigerator sounds were convolved with the binaural impulse response measured at 7 m from a source in a 100 m^2 apartment, which is a common size in Korea. Its reverberation time was around 0.7 s at 500 Hz. These sounds were reproduced in a test chamber using a stereo dipole technique including cross-talk canceling filters. They were played for 30 s in the range of 49–62 dBA. The original sound pressure levels were increased to make the subjective judgment more easily. The subjective evaluation test was based on nine-point scales on which participants scored the "noisiness"of each refrigerator. Nine university students with normal hearing took part in the subjective test. For each participant, the sound from the 24 refrigerators was evaluated in 13 minutes.

The correlation between the average of the subjective scales of noisiness for the nine subjects and the noisiness of each of the nine subjects was more than 0.70. The average of the subjective scales of noisiness for the nine subjects is used hereafter.

2.2 Noisiness and psychoacoustical parameters

First, the psychoacoustical parameters (loudness, sharpness, roughness, and fluctuation strength) were used to clarify the acoustical characteristics of the refrigerator noise. The time interval between the spectra was set at 10 ms for the calculation of roughness and fluctuation strength. Mean values of loudness and sharpness were used to describe the acoustical property of the sound.

Each refrigerator sound was divided into two parts: the starting (0–5 s) and stationary (5–30 s) phases because the starting phase of refrigerator noise includes a click sound, rapid increase of volume, and a change of the pitch. The correlation between noisiness and psychoacoustical parameters for the starting and the stationary phases are listed in Table 1. Regarding the starting phase, loudness and fluctuation strength revealed a significant correlation with noisiness. Noisiness increases as loudness and/or fluctuation strength increases. Correlations for the stationary phase indicated that loudness had a significant correlation with noisiness. Roughness and fluctuation strength also showed significant correlation with noisiness. Comparing the starting and stationary phases, there is a greater contribution of roughness to the initial phase than that to the stationary phase.

2.3 Noisiness and ACF parameters

The ACF parameters were also used to clarify the acoustic characteristics of refrigerator sound. The ACF is calculated at every given integration interval after passing through an A-weighting network. The start of each integration interval was delayed for a short time (the moving step). Moving analysis is effective in describing the temporal properties such as transition, propagation, decay, and fluctuation of a sound. The physical parameters are extracted as fine structures of ACF. The first and second parameters are delay time and the amplitude of the first dominant peak of the ACF, τ_1, and ϕ_1. The third parameter is the effective duration of the envelope of the ACF, τ_e. This factor is defined by the 10-percentile delay representing a kind of repetitive feature or reverberation within the source signal itself. The definitions of these factors are illustrated in Fig. 1. In this study, the integration interval was 3.0 s and the running step was 0.1 s. Average measures were obtained for the left and right ear signals. The standard deviation of each parameter was also calculated to express the temporal variation of the parameter.

Similar to the psychoacoustical parameters, each refrigerator sound was divided into two parts: the starting and stationary phases. The correlation between the noisiness and the ACF parameters for the starting and the stationary phase is listed in Table 2. Regarding the starting phase, $\Phi(0)$, the standard deviation of τ_1 indicated significant correlation with noisiness. Noisiness increases as $\Phi(0)$ and/or the deviation of τ_1 increases. Correlations for the stationary phase indicate that $\Phi(0)$ had a significant correlation with noisiness. No significant correlation was observed with the standard deviation of the parameters of the stationary phase.

3. SQ (Sound Quality) Indices for noisiness

3.1 SQ Index for psychoacoustical parameters

In the previous section, the relationship between noisiness and each parameter was investigated. Here, the contribution of each parameter to noisiness was investigated by using multiple regression analysis. SQ Indices using the significant factors were examined. To obtain an optimal equation, the stepwise multiple regression was examined. The best combination of variables in respect to the correlation between the noisiness and the psychoacoustical parameters for the starting phase was found to be loudness ($r = 0.75$, $p < 0.01$).

$$SQ_{starting} = 0.33Loud+3.78 \quad (2)$$

Table 1. Correlation between noisiness scale and the psychoacoustical parameters.

	Loudness	*Sharpness*	*Roughness*	*Fluctuation strength*
Starting phase	0.75**	0.08	0.30	0.67**
Stationary phase	0.83**	0.10	0.45*	0.44*

**: p < 0.01; *: p < 0.05

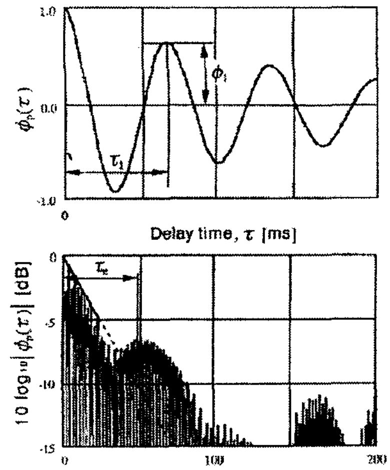

Fig. 1. Definition of ACF parameters. (a) τ_1 and ϕ_1; and (b) τ_e.

Table 2. Correlation between noisiness scale and ACF parameters.

	$\Phi(0)$	τ_e	τ_1	ϕ_1
Starting phase (average)	0.76**	0.13	0.17	-0.16
Starting phase (S.D.)	0.46*	0.14	0.62**	0.23
Stationary phase (average)	0.71**	0.06	0.17	-0.03
Stationary phase (S.D.)	0.01	0.15	0.54	-0.23

**: p < 0.01; *: p < 0.05

In addition, the best combination of variables in respect to the correlation between the noisiness and the psychoacoustical parameters for the stationary phase was found to be loudness and roughness ($r = 0.87$, $p < 0.01$). The standardized partial regression coefficients of loudness and roughness in Eq. (3) were 0.77 and 0.28, respectively, and were statistically significant ($p < 0.05$).

$$SQ_{stationary} = 0.50Loud+0.75Rough+1.26 \quad (3)$$

3.2 SQ index for ACF parameters

In a similar manner to the psychoacoustical parameters, SQ Indices using the significant factors were examined. Here, the standard deviations of ACF parameters were also included in the analyses. To obtain an optimal equation, the stepwise multiple regression was examined. The best combination of variables in respect to the correlation between the noisiness and ACF parameters for the starting phase was found to be $\Phi(0)$, ϕ_1, sd_$\Phi(0)$ and sd_τ_1 ($r = 0.93$, $p < 0.01$). The standardized partial regression coefficients of $\Phi(0)$, ϕ_1, sd_$\Phi(0)$ and sd_τ_1 in Eq. (5) were 0.78, −0.28, 0.22, and 0.23, respectively, and these coefficients were statistically significant ($p < 0.05$).

$$SQ_{starting} = 0.26\Phi(0)-1.80\phi_1+0.20sd\_\Phi(0)+0.56sd\_\tau_1+8.00 \quad (5)$$

In addition, the best combination of variables in respect to the correlation between the noisiness and ACF parameters for the stationary phase was found to be $\Phi(0)$ and ϕ_1 ($r = 0.87$, $p < 0.01$). The standardized partial regression coefficients of $\Phi(0)$ and ϕ_1 in Eq. (6) were 1.01 and −0.50, respectively, these coefficients were statistically significant ($p < 0.05$).

$$SQ_{stationary} = 0.34\Phi(0)-3.63\phi_1+11.28 \quad (6)$$

Equations (5) and (6) give comparisons between the starting and the stationary phases of the refrigerator sounds. The sd_$\Phi(0)$ and sd_τ_1 appear only in Eq. (6) for the starting part, while $\Phi(0)$ and ϕ_1 appear in both equations. The division between the starting and stationary part was reasonable regarding ACF parameters because the starting part contains more fluctuations in terms of loudness and pitch. In both equations, $\Phi(0)$ had the largest contribution to the noisiness.

4. Ending phase of the refrigerator noise

Regarding the ending phase of the refrigerator noise, only the objective parameter analyses were conducted because the ending phase is the termination of the noise and it does not seem to affect the noisiness. Typical examples of the ACF parameters are shown in Fig. 2.

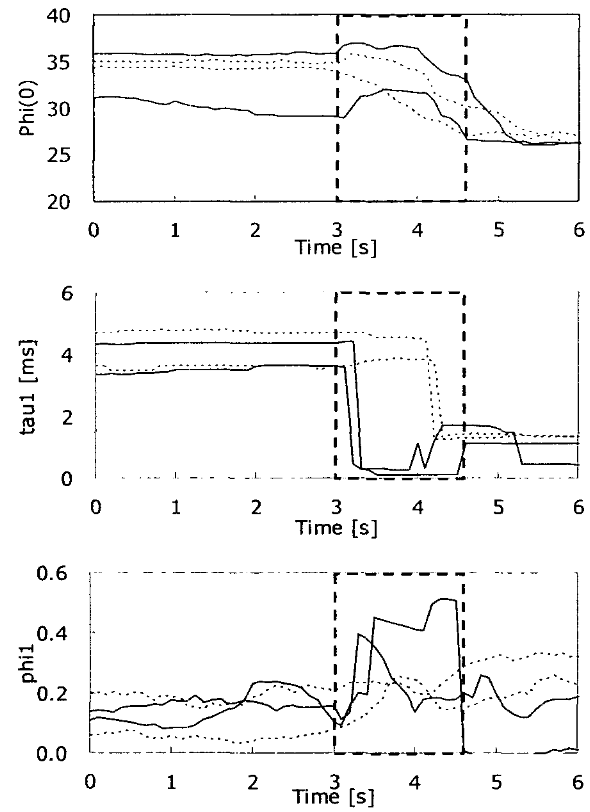

Fig. 2. Examples of the ending phase of refrigerator noise with rattle sounds (——) and fade-out sounds (------) in terms of the ACF parameters.

5. Discussion

Figure 3 shows examples of the refrigerator noises with more noisiness and less noisiness in terms of the ACF parameters. The refrigerators with greater noisiness indicate a greater Φ(0) and its respective fluctuation. Also, these noises indicate a greater fluctuation of τ_1. On the other hand, refrigerators with less noisiness indicate a smaller Φ(0) and its respective fluctuation. Also, these noises indicate smaller fluctuation of τ_1. These results mean that greater loudness, greater fluctuation of loudness, and greater fluctuation of pitch of a given refrigerator sound, result in higher noisiness. Regarding ϕ_1, the refrigerator noises with more perceived noisiness indicate relatively smaller ϕ_1 (< 0.4) and the refrigerator noises with less perceived noisiness indicate relatively larger ϕ_1 (>0.4). This means that the refrigerator noise that contains more noise components (large fluctuation) results in higher ratings of perceived noisiness.

Our previous study focused on the stationary part of refrigerator sounds and investigated the SQ Index for psychoacoustical parameters[(4)]. Same as the present study, loudness and roughness were significant factors. In addition, the SQ Index for ACF parameters can be calculated from refrigerator sounds which were used in the study. Also, same as the present study, Φ(0) was a significant factor. The standardized partial regression coefficients of a_1, a_2, a_3 and a_4 in Eq. (4) were 0.34, −0.0001, 0.02, and 0.49, respectively.

6. Conclusions

Subjective evaluations of refrigerator noise were investigated. Here, we employed psychoacoustical and ACF parameters as possible measures for describing the noisiness of refrigerator noise. The results of the observed relationships between noisiness and the psychoacoustical and the ACF parameters show that important factors for evaluating noisiness are loudness and roughness of stationary phase. Regarding the amplitude fluctuation of refrigerator sounds, fluctuation strength is more important in the starting phase, and roughness is more important in the stationary phase. Among the ACF parameters, Φ(0), ϕ_1, and the standard deviations of Φ(0) and τ_1 of the initial phase are important.

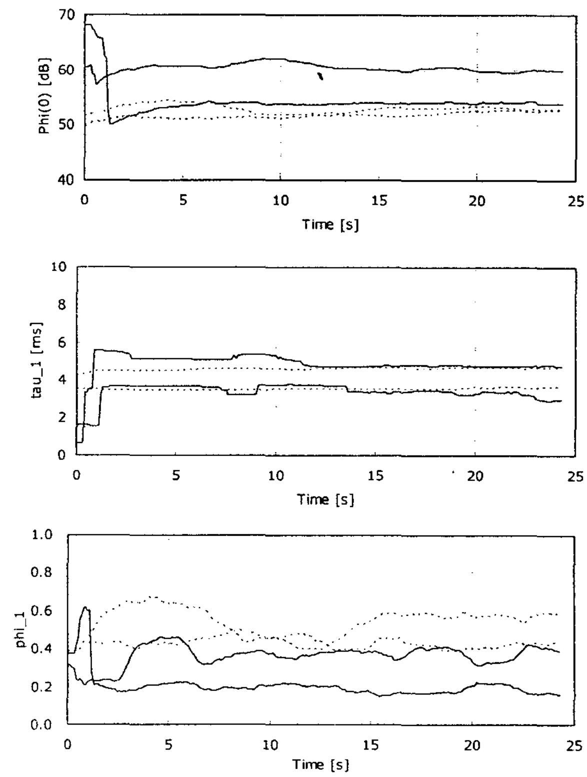

Fig. 3. Examples of the refrigerator noise with more noisiness (——) and less noisiness (------) in terms of the ACF parameters.

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