ABSTRACT
A prediction model for the sound quality of refrigerator noise was proposed by investigating subjective and objective attributes of the noise [Jeon et al. (2007) Appl. Acoust.]. In the present study, the just noticeable difference (JND) of each sound quality metric - loudness, sharpness, roughness and fluctuation strength - which constitute the prediction model was investigated. Loudness of recorded sound samples from five refrigerators was varied according to constant intervals in sound pressure levels. Sharpness was also changed at 14-16 barks in order to provide experimental sounds. Roughness and fluctuation strength were changed by varying amplitude modulation frequencies in time domain. Auditory experiments were conducted to discriminate the JNDS of sound quality metrics by method of limit. The results indicated that JNDs of loudness and sharpness were 0.50 sone and 0.08 acum, respectively. JNDS of roughness and fluctuation strength were also found as 0.03 asper and 0.01 vacil, respectively. These results can be applied to estimate the perceivable difference of sound quality metrics.

INTRODUCTION
Annoyance of household appliance noise such as refrigerator noise is influenced not only by sound pressure level but also by frequency and time variation of the noise, and also by human auditory characteristics. This is the reason why psychophysical approach should be made as far as sound quality enhancement of appliance noise is concerned [1-2]. In order to investigate sound quality characteristics of refrigerator noise considering real living environments, previous study [3] was done and Zwicker’s loudness, sharpness, roughness and fluctuation strength [4] were found as dominant sound quality metrics describing subjective evaluations.

However, just finding and characterizing dominant sound quality metrics of specific sound is not sufficient. In order to improve sound quality of the noise effectively, just noticeable difference (JND) of each metrics should be investigated and also methodologies for the investigation should be defined. Studies on JND are mostly dealt with in the psychoacoustic field, and are mainly concentrated on intensity, frequency and duration discriminations. Pure tone, complex tone, or white noise is applied for the JND studies [5-9] but little is known about the crimination of sound quality metrics using actual noise.

Methodologies of JND investigation are classified to method of limit, method of adjustment, and method of constant stimuli classically [10], and simple and transformed up-down methods are also applied to provide unbiased results [11]. Method of limit has advantages of simple procedures of experiments and analyses but requests sufficient pilot-test as its limitations. Whereas, biased results can be reduced by applying transformed up-down method but procedure of the method is complicated comparing that of method of limit.

In the present study, JND of sound quality metrics such as loudness, sharpness, roughness and fluctuation strength was investigated applying refrigerator noise and method of limit was used as methodology of discrimination measurements. Experimental sounds were provided by convolution between refrigerator noise recorded in an anechoic chamber and impulse response measured in an actual living room. Value of sound quality metrics of the sounds was varied and auditory tests were conducted to find JND of each of the metrics. JND was determined when more than 75% of subjects participated in the tests showed differential discrimination response.
[11-12]. Results of the present study can be applied to the sound quality prediction model proposed in the previous study [3] in order to find the value of minimum enhancement in subjective responses.

SOUND MEASUREMENTS AND AURALIZATION

Sound measurements
Noise of twelve side-by-side type refrigerators was recorded in an anechoic chamber. As shown in Fig. 1, four half-inch microphones were located at 1 m apart from the front, back and both lateral sides of refrigerator. Full length noise of refrigerator operation cycle was recorded simultaneously at the height of 1 m using the four microphones. Steady-state noise of the rear position was applied to the present study because it showed the largest sound pressure level.

![Figure 1.- Microphone positions in an anechoic chamber, O: microphone](image)

Auralization with impulse response of actual living room
Impulse response of actual living area was measured in a 100 m² apartment house. Omni-directional loudspeaker was located at the position of refrigerator in the kitchen instead of actual refrigerator, and Head and Torso Simulator (HATS) was positioned in living room, 7 m apart from the loudspeaker. In order to input the information of actual living area to the anechoic sound, the refrigerator noise was convolved with the impulse response. A total of five refrigerator noises were auralized by the actual room information for the loudness JND experimental sounds, and another three refrigerator noises were auralized for the sharpness, roughness, and fluctuation strength experimental sounds, respectively.

PREPARATION OF EXPERIMENTAL SOUNDS

Loudness and sharpness
In order to provide sounds of loudness JND experiment, sound pressure level of auralized sounds of the five refrigerators (A-E) were varied to change loudness. As shown in Fig. 2, five sounds indicated as thin solid lines were created from the original sound indicated as thick solid line in the graphs. Loudness difference between each of the neighbouring sounds was around 0.20 sone and maximum loudness difference between original sound and created sounds was around 1.40 sone.

![Graphs](image)
Figure 2.-(a), (b), (c) Loudness spectrum of experimental sounds of 3 refrigerators among the 5 total specimen for loudness JND experiments, \(-\) original sound; \(-\) created sounds.

In case of sharpness, sound pressure level of original sound was varied only at 14-16 Bark. By changing envelope of loudness spectrum, sharpness was controlled to vary in about 0.02 acum steps as shown in Fig. 3. The maximum sharpness difference between original sound and created sounds was around 0.10 acum and loudness difference was quite small that biased responses influenced by loudness difference were excluded.

Figure 3.- Loudness spectrum of experimental sounds for sharpness JND experiments, \(-\) original sound; \(-\) created sounds.

Roughness and fluctuation strength
Amplitude of refrigerator noise was modulated in time domain to create experimental sounds of roughness and fluctuation strength JND tests. Only modulation frequency was different between roughness and fluctuation strength experimental sounds in the procedure of modulations. Value difference between neighbouring sounds was 0.01 asper and 0.003 vacil for roughness and fluctuation strength, respectively. Maximum range of roughness between original sound and created sounds was around 0.09 asper, and that of fluctuation strength was about 0.025 vacil as shown in Fig. 4.

Figure 4.- (a) Roughness spectrum of experimental sounds, (b) Fluctuations strength spectrum of experimental sounds, \(-\) original sound; \(-\) created sounds.
SUBJECTIVE EVALUATIONS

Outline of auditory experiments
Auditory experiments were conducted to discriminate the difference between original sound and sound quality varied sound in terms of each of the sound quality metrics. A method of 2-Interval and 2-Alternative Force Choice was applied for these evaluations and also method of limit was used obtaining subjective responses as shown in Fig. 5. All of the subjects were asked to answer which sound is louder, for example of loudness JND test, or both are the same by listening pairs of original sound and sound quality varied sound. The order between original sound and varied sound was randomized in each pairs and all of the pairs were also randomly presented. JND was determined as the value difference of sound quality metric that more than 75% of subjects discriminated the difference.

Forty subjects were participated for loudness and sharpness JND tests, and two experts for roughness and fluctuation strength JND tests. The forty attended the tests for one time, but the two experts conducted the tests ten times per person. All of the experimental sounds were presented using headphone in a semi-anechoic chamber and presentation sound level was adjusted as the same to the sound level of refrigerator noise in actual living room position.

Results of the experiments
Fig. 6 indicates the JND results of each of the sound quality metrics. The abscissa represents value difference between original sound and sound quality varied sound, and the ordinate indicates percentage of subjects’ differential discrimination responses in Fig. 6. In case of loudness, more than 75% of the subjects started to recognize the loudness difference when the difference was around 0.5 sone. Therefore, JND of loudness can be explained as 0.5 sone and that of sharpness was obtained as 0.08 acum with the same procedure. It was found that the JND of roughness and fluctuation strength was around 0.03 asper and 0.01 vacil, respectively, by the ten-times of results of the two experts. These results indicate that loudness, sharpness, roughness and fluctuation strength should be reduced more than 0.5 sone, 0.08 acum, 0.03 asper and 0.01 vacil, respectively, in order to improve the overall sound quality characteristics of the noise to the perceivable level.
CONCLUSION

In this study, just noticeable difference of sound quality metrics was investigated by applying refrigerator noise. JND of loudness, sharpness, roughness and fluctuation strengths was obtained as about 0.5 sone, 0.08 acum, 0.03 asper and 0.01 vacil, respectively, by conducting auditory tests of differential discriminations. More accurate and effective sound quality control will be possible by applying the results of JND of each metrics, because the results provide substantial ideas for sound quality enhancements considering subjective responses on actual appliance noise. Also, methodologies used in this study can be applied to other researches on sound quality improvement of appliance noise such as air-conditioning sound. In order to validate the JND results, advanced methodologies such as transformed up-down method rather than method of limit can be introduced for subjective differential discriminations as a further study. We anticipate results of this study and further studies will contribute defining and generalizing methodologies on JND investigations of sound quality metrics.

References: