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Evaluation of Sound Quality for Ergonomic Design of Movable Parts in a Refrigerator

Seong Yeop Kang[*], Sae Rom So[*], Gun Ou Kim[*], Ji Hoon Kim[*], Sang Hu Park[**,#]

[*]Graduate School of Mechanical Engineering, Pusan National University,
[**]School of Mechanical Engineering, ERC/NSDM, Pusan National University

냉장고 동작부품의 소음특성 분석을 통한 감성품질 개선

강성엽[*], 소새롬[*], 김건우[*], 김지훈[**], 박상후[**,#]

[*]부산대학교 기계공학부 대학원, [**]부산대학교 기계공학부/정밀정형 및 금형가공 연구소

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ABSTRACT

We propose a method for evaluating sound quality quantitatively to develop high-level home appliances (HA). Generally, a refrigerator has diverse movable parts such as slider, drawer, and folding shelf. Therefore, an engineering treatment to control the noise quality is considered as one of key technologies for a higher level refrigerator. Among the movable parts, we have selected a folding shelf as an example, which is commonly setup inside of a home refrigerator for increasing space convenience, to control the noise quality. However, it is known that its noise level is very high comparing to other movable parts when folding or unfolding actions. In order to evaluate and compare the noise quality, we have tested different eighteen models, and have suggested an impact sound quality index (ISQI) based on subjective evaluation data obtained experimentally by thirty two evaluators. The ISQI was formulated using three sound quality elements (noise peak, raising time, impact duration) to determine psycho-acoustic properties. Through this work, we developed an evaluating process and ISQI that was verified the usefulness by comparing the test results of personal perceptions given by evaluators with the prediction value of ISQI. We showed a good relations between them, so we believe that the proposed method and ISQI can be utilized to control of the noise quality of HA effectively.

Key Words : Impact Sound(충격 소음), Refrigerator Movable Part(냉장고 동작 부품), Sound Quality Index(음질 평가지표), Personal Evaluation(주관적 평가)

1. Introduction

Shelves or drawers in a refrigerator are opened and closed according to the consumer's demands. Shelves can be designed as foldable for the efficient use of the space. However, these same shelves might generate noise due to the impact or friction between parts through the relative motion. Thus, it is necessary to have a noise management system

Corresponding Author : sanghu@pusan.ac.kr
Tel: +82-51-510-1011, Fax: +82-51-510-1973

generated for products with high-end quality. Accordingly, various studies have been conducted on low noise structural design, noise assessment methods, and sound quality characteristics[1~4].

Most existing studies on noise management have been conducted for cars and have involved features such as objective quantification of door closing noises, development of sound quality for luxury cars, analysis of intake and exhaust systems for noise improvements, and development of a sound quality index according to tire patterns[5~8].

Loudness, sharpness, roughness, and fluctuation strength are regarded as four typical indices of sound quality[9~11]. The four sound quality indices evaluate noise of normal signals that are maintained for a certain period, but they have difficulties evaluating the noise of transient signals that are generated instantaneously, such as impact sound. In addition, existing studies are limited to cars or washing machines whose noises are relatively loud, but few studies have been conducted on the noise management of indoor appliances such as refrigerators.

For international and national specifications that express a level of noise, a decibel (dBA) has been used as the evaluation unit that, after calibration, represents equal loudness in the frequency band as the human auditory structure experiences[12]. However, this evaluation unit n considers only the most basic functions among humans' noise perception variables and is not suitable to evaluate the impact of sounds that have other sound quality factors. This study proposed a method to analyze the sound quality of an impact sound that was generated as a relative motion between parts in a refrigerator for households. In particular, this study proposed a method of sound quality analysis for operating noise using an example of a folding shelf that was regarded as the loudest noise among the operating parts in a refrigerator.

The materials used in the internal operating parts in a refrigerator are mainly plastic, and the folding shelf is operated as a sliding type. When users spread the shelf out by pulling on the front end of the folding shelf, collision occurs between some components; due to the relative motion between moving and fixed portions, noise is inevitably generated. The loudest noise occurs during the impact portion of the unfolding motion. Fig. 1 shows the folding shelf structure, operating mode, and impact portion. When the shelf is spread, the moving portion moves horizontally and subsequently makes an impact noise as it rides up over the curve and collides with the vertical support. Thus, as a structural design alternative, a damping mechanism is applied to the place of impact and a slope in the curve section may be given. It is critical to have an evaluation index of sound quality quantitatively to be able to ascertain whether the impact noise has really improved for actual consumers according to the structural design variables.

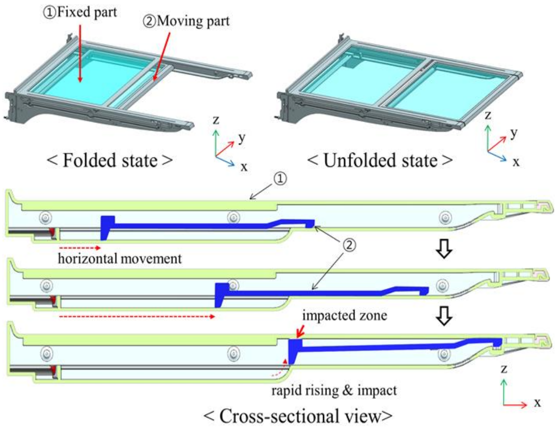


Fig. 1 Schematic diagram on structures of a folding shelf (top), and horizontal moving of part ② and impacting mechanism

The measurement results of the impact noise generated during the operation of the folding shelf showed that the impact noise was an impulse signal where the sound pressure level was measured in a short period of time. The frequency analysis results at the highest sound pressure level exhibited that the impact noise was measured at the entire frequency band constantly. Figs. 2 and 3 show the measured values of sound pressure level and the measured frequency band data when the folding shelf is spread using a motor at a speed of 0.5 m/s, which is the speed with which consumers are generally assumed to pull the shelf. The maximum impact noise was generated at the impacted zone shown in Fig. 1, and it was approximately 76.5 dBA. This noise level should be irritating to consumer's ears in terms of the sound magnitude.

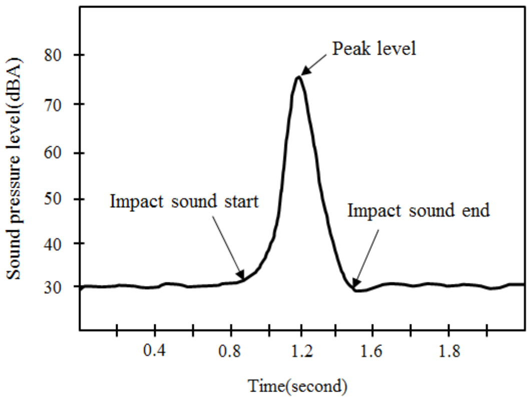


Fig. 2 Impact sound level generated when folding shelf is spreaded

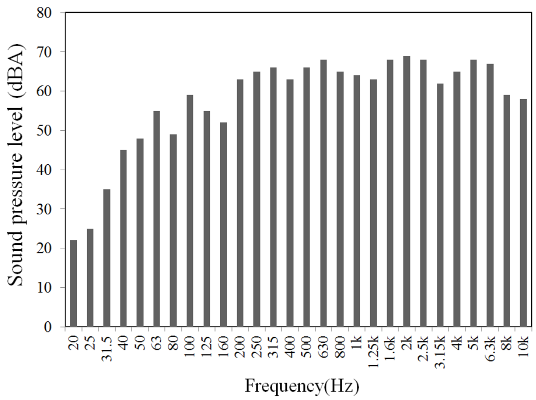


Fig. 3 Impact sound transformed to frequency domain

2. Analysis of sound quality characteristics

2.1 Sound quality characteristics

Impulsiveness is one of the impact sound characteristics, and it is used to quantify impulse characteristics[13]. In the algorithm that calculates impulsiveness, the impulse peak level (Pl), which is the highest sound pressure level based on the measured signals; the impulse rise time (Rt) that it takes to reach the peak level; and the total impulse duration (Id) are used[14]. The impulse peak level refers to the largest value of the impulse signal, impulse rise time refers to the time taken to reach the peak level, and total impulse duration refers to the total time of the impulse signal. Thus, in measuring the sound quality of impact sound, both the impulse peak and the size of rising time are important. This is different from general noise quality, so it is difficult to evaluate the impact sound quality simply through the noise loudness level.

Since the impulse peak level, impulse rising time, and total impulse duration are independent variables, this study improved analytical precision by selecting them as the sound quality factors of impact noise.

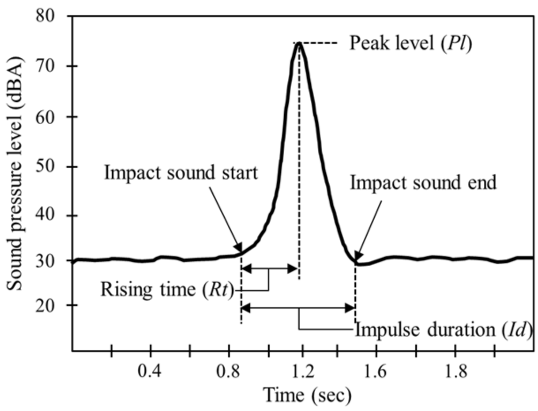


Fig. 4 Schematic diagram of impact sound elements

Table 1 Measurement of sound quality elements

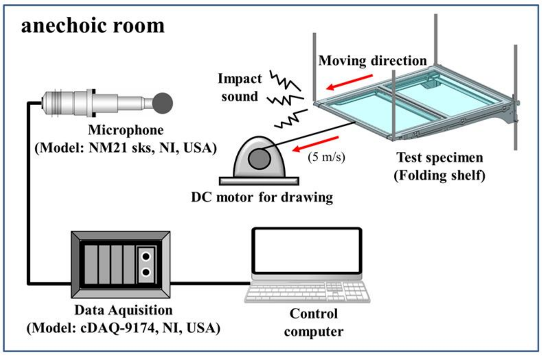
Sound Quality Elements	values
Peak level	76.5 dBA
Rising time	0.375 sec
Impulse duration	0.775 sec

Fig. 4 shows the meaning of the sound quality values with regard to the aforementioned impulse impact noise. Table 1 summarizes the impact sound from the folding shelf measured in Fig. 2 by the sound quality factor.

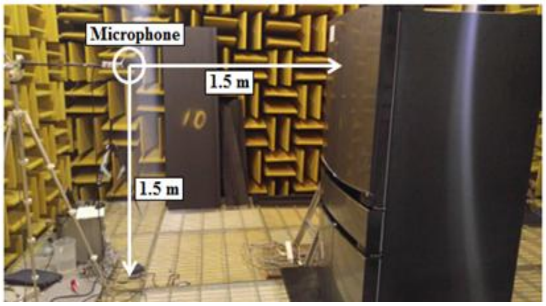
2.2 Configuration of the experiment device

The measurement and recording of the sound quality factor data during the operation of the folding shelf are shown in Fig. 5. The noise data measurements and recording were conducted in an anechoic room that was optimized to measure the refrigerator noise. The recording was conducted by minimizing the noise of the actual impact sound using a microphone. Since the impact varied depending on the spread speed of the folding shelf, and the impact sound differed accordingly, a DS motor device was configured to implement the same speed (0.5 m/s).

A total of 18 folding shelves used in commercial refrigerators were used to measure the impact sound generated during the spread operation comparatively. In addition, data of three sound quality factors for each model were derived using the recorded impact sound over time. Table 2 summarizes the measurement data for the three sound quality factors selected as the evaluation indices of impact sound generated by the 18 folding shelves for refrigerators in this study. Three sets of measurements for each model were conducted and a mean was calculated. No significant difference was revealed during the repeated measurements of the same model, which was due to the same pulling speed maintained by the DS motor control.



(a)



(b)

Fig. 5 (a) Schematic diagram of impact sound measuring setup, and (b) photograph of impact sound measured in anechoic room

2.3 Evaluation of emotional sound test

The objective evaluation of sound quality is difficult because every person has different preference. Thus, this study performed a sound evaluation through the semantic differential method (SDM) to objectify the evaluation. In the SDM, evaluators select emotional adjective terms felt by him/her with regard to the evaluation target (impact sound) when quantitative evaluation is difficult through the objective evaluation criteria[15]. Thus, this study selected the emotional adjective term “displeasure” and 32 household wives in their 30s living in Busan who used electronic appliances often as the evaluators. The survey was conducted as follows: evaluators heard the impact sound of the 18 folding shelves from model No. 1 to 18 sequentially, one time, and then heard each again model three times. Evaluators were then asked to record the level of “displeasure” caused by the impact sound by scoring it from 1–10 on the survey questionnaire. The higher the displeasure was, the higher the score was. Fig. 6 shows the means of the scores in the emotional sound test on the impact sound of the 18 folding shelf models in refrigerators.

In the survey questionnaire items, evaluators recorded their scores from 1–10 according to the displeasure felt from the shelf model number. If the score was larger, evaluators felt more displeasure. To raise the reliability of the emotional sound test about displeasure, evaluators had to recode their scores within five sec after listening the impact sound.

Table 2 Impact sound data of folding shelves of 18 models for three sound quality factors.

Models	Peak level (dBA)	Rising time (sec)	Impulse duration(sec)
1	75.9	1.125	1.325
2	77	0.85	1.875
3	85	1.25	1.75
4	74.9	0.875	1.25
5	79.7	0.75	0.875
6	76.9	0.75	1.5
7	77.1	0.625	1.125
8	76	0.75	1.125
9	76.7	1.25	1.5
10	74	0.765	1.875
11	75.1	0.85	1.375
12	79	0.35	0.875
13	77.8	0.625	0.875
14	76.3	0.85	1.125
15	81.5	0.625	1.25
16	76.2	0.875	1.875
17	60.7	0.5	1.875
18	77.9	0.75	1.125
Max	85	1.25	1.875
Min	60.7	0.35	0.875
Mean	76.5	0.801	1.365

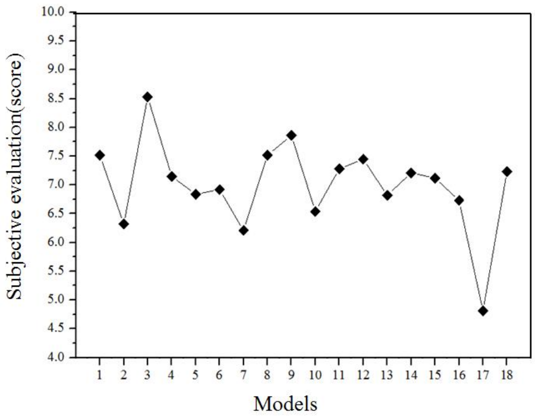


Fig. 6 Variation of subjective raking scores of displeasure on 18 folding shelves

2.4 Derivation of the emotional noise evaluation index

The simultaneous equation matrix (sound quality metrics) of the subjective emotional evaluation scores was configured through the evaluation of emotional sound test of the three selected impact sound quality factors using the impact level. The approximate expression of the sound quality metrics was calculated using the least square method[16~17] to derive the emotional evaluation index of the impact sound from the operating parts in a refrigerator. As a method to obtain the approximate expression using the least square method, based on the objective impact sound data and subjective emotional evaluation scores, coefficients C1 to C3 were calculated as presented in Eqs. (1) and (2).

$$\begin{bmatrix} Pl & Rt & Id \\ \vdots & \vdots & \vdots \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \\ C_3 \end{bmatrix} = \begin{bmatrix} Se \\ \vdots \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} C_1 \\ C_2 \\ C_3 \end{bmatrix} = \left(\begin{bmatrix} Pl & Rt & Id \\ \vdots & \vdots & \vdots \end{bmatrix}^T \begin{bmatrix} Pl & Rt & Id \\ \vdots & \vdots & \vdots \end{bmatrix} \right)^{-1} \begin{bmatrix} Pl & Rt & Id \\ \vdots & \vdots & \vdots \end{bmatrix}^T \begin{bmatrix} Se \\ \vdots \end{bmatrix} \quad (2)$$

The final emotional evaluation index, which is called the impact sound quality index (ISQI) and is calculated with regard to impact sounds using the least square method, is presented in Eq. (3).

$$ISQI = C_1Pl + C_2Rt + C_3Id = 0.0838\,Pl + 1.7737\,Rt - 0.609\,Id \quad (3)$$

The analysis results of the derived index Eq. (3) showed that as the peak level (Pl) becomes smaller, rising time (Rt) becomes shorter, and as total impact duration (Id) grows, the displeasure index felt by users became lower.

It is not easy to predict human emotion by quantitative values accurately, and predictions may have errors. The previously measured impact sound data were substituted into the evaluation of impact sound quality index (ISQI) derived in this study, and the results were compared with the subjective emotional evaluation test results. Fig. 7 shows the evaluator's values obtained from the tests and the ISQI prediction values for the 18 types of folding shelf evaluation models. Error was different depending on the model. The minimum error was 0.09%, which was very close to the actual test value, but some errors exceeded 10%. The reason for this large error needs to be analyzed in the future, and the ISQI needs to be verified by changing the number of evaluators or evaluation groups.

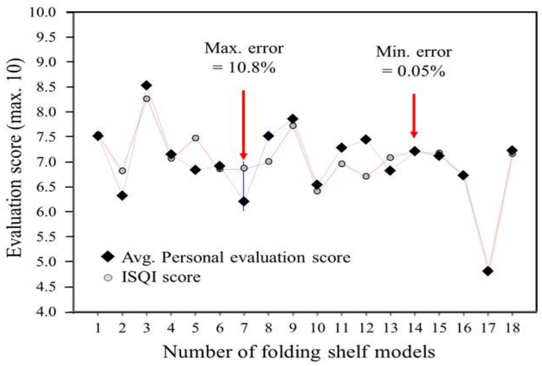


Fig. 7 Comparing of error amounts between personal evaluation score and ISQI score on eighteen folding shelves

3. Design of the improvement of the operating parts in a refrigerator

The folding shelf structure was improved to generate the impact sound whose displeasure index was the lowest by users, based on the derived emotional noise evaluation index. The noise factors that affected the duration of impact sound generation are closely correlated with the material properties of the product. As the damping coefficient of the material becomes larger, the duration becomes shorter, so that the duration of impact sound becomes shorter as well. However, the complete replacement of product’s properties is generally difficult due to high costs. Thus, this study aims to improve the impact sound quality through structural rather than material change in the operating parts.

As shown in Fig. 1, sudden impact occurs between the folding shelf and the supports that hold the shelf vertically during the spreading process.

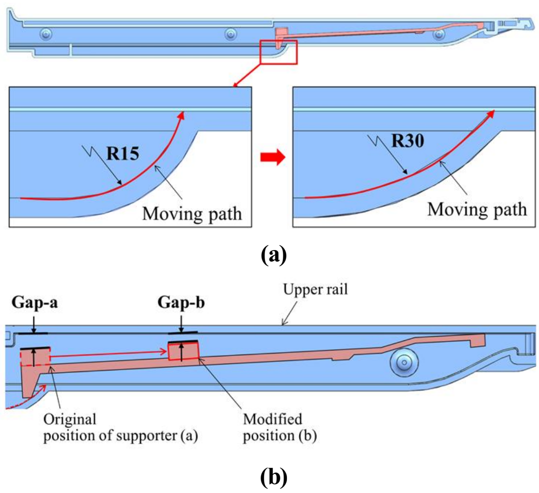


Fig. 8 (a) Improved model A with radius of 30 mm from 15 mm for delay the moving path, and (b) improved model B with change of position of supporter from a to b for decrease of gap between supporter and upper rail (Gap-a to Gap-b)

Thus, the slope of the curve surface was changed as shown in Fig. 8(a) to increase impact time in the new model. In addition, the vertical fixed support attached to the shelf's moving portion was placed at a different location, thereby reducing the impact amount.

Fig. 8(a) shows the model (improvement-A model) that reduces the impact force at the place of impact by designing a curved operating surface with a gradual slope structure by making the radius R value large, which was a sharply rising part. Furthermore, Fig. 8(b) shows the improved model (improvement-B model) that makes the impact sound lower than that of existing models by reducing the impact force. The improvement-B model decreases the speed of impact when the shelf is riding the drive rail by moving the vertically fixed support from a to b, which is one quarter of the location of the drive part length, in addition to the application of the improvement-A model.

Table 3 presents the sound quality factor data, evaluation values from the emotional evaluation of sound test, and evaluation index values of emotional noise in the existing model and the two improved models.

The sound evaluation test, using the same aforementioned method with the same evaluators, was conducted after fabricating the impact sound quality improvement models through structural modifications. The test results verified that the improvement models reduced the noise more than the existing models through the ISQI.

Table 3 Comparison of original model with improved model A and B

	Original model	Improved model A	Improved model B
Peak level	76.3 dBA	72.5 dBA	69.1 dBA
Rise time	0.85 sec	0.85 sec	0.85 sec
Impulse duration	1.12 sec	1.11 sec	1.12 sec
ISQI	7.22	6.90	6.61
Personal evaluation	7.21	6.77	6.51

Thus, the effectiveness of the evaluation method proposed in this study was verified, and this study proved that sound evaluation can be represented with quantitative values.

4. Conclusions

This study developed a quantitative emotional noise evaluation index to assess and predict “displeasure,” which was a subjective emotion caused by the impact sound that occurred when the driving part inside a refrigerator door was moved. The sound quality factors of impact sound, peak level, impulse rise time, and total impulse duration were derived using impact level, and an emotional noise evaluation index was developed after measuring and recording the impact noise data, selecting survey evaluators, and conducting an emotional evaluation survey[18~20]. The experiment results showed the need for design measures that reduce peak level and impulse rise time and increase total impulse duration to alleviate the displeasure felt by users from the folding shelf based on the emotional noise evaluation index.

Thus, two improvement models were proposed through the design concept derived through the ISQI, and re-evaluation tests were conducted using the same method after fabricating the improved models. The final evaluation results verified that the improvement models improved the impact sound quality. Thus, the evaluation method proposed in this study was proven. However, studies on reduction of error in quantitative prediction values of the proposed ISQI are needed, and future research should change the evaluator groups or the number of evaluators for this purpose.

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