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Development of Psycho-Acoustic Indices for Vehicle Door Latch and Window Lift Systems

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Development of Psycho-Acoustic Indices for Vehicle Door Latch and Window Lift Systems

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ABSTRACT

Development of Psycho-Acoustic Indices for Vehicle Door Latch and Window Lift Systems

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In this thesis, perceived sound quality of electro-mechanical devices in vehicles is studied. Sounds of electro-mechanical devices in vehicles can be divided into simple impulsive sound and complex sound. Sound quality of simple impulsive sound is studied base on a case of door latch, and sound quality of complex sound is studied based on a case of window lift. First, an index that evaluates the sound quality of the door latches was developed and the modification of module was conducted to improve sound quality based on the results. To conduct the jury evaluation, various operating sounds of door latches were used. Through the results of the jury evaluations, it was found out that loudness and sharpness related metrics are dominant in

the psycho-acoustic index we developed. In addition, this research investigates the main transfer path of operating sounds through sound field visualization and concludes what could reduce the impact sound of the door latch. Therefore, improvement of the door latch's sound quality could be verified by using the psycho-acoustic index. Next, I developed a psycho-acoustic index for assessing the sound of window lift modules during operation. Window lift operations were classified as "ascent" and "descent," and sound quality indices were developed for each operation and compared. In order to quantify the subjective sound quality preferences, correlations between factors were determined through factor analysis. For ascent, the relevant factors were determined to be described by luxuriousness and uniformity. For descent, the relevant factors were explained by luxuriousness and strength. Correlations between each factor and previously developed sound quality metrics were also analyzed to finally derive an equation that explains the preference in terms of sound quality metrics.

Keywords: Sound Quality, Electro-mechanical devices, Door latch, Window lift, Motor sound, Semantic differential, Factor analysis

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CHAPTER 1

INTRODUCTION

The study of automobile noise has conventionally been based on classifying and reducing the main noise sources in automobiles: engine and road noise. This is because these noises have large amplitudes and long durations, so they are the most audible within the vehicle cavity. Engine and road noises are characterized by a relatively low frequency band of less than 500 Hz [1-6]. However, following the recent increase in high-end automobiles, numerous electro-mechanical devices have been installed on automobiles: from power windows, which were developed at a very early stage, to panoramic sunroofs. The noises from these electro-mechanical devices have characteristics distinct from those of the previous automobile noises because they are actuated by motors. Thus, they are a new kind of noise source. The sound generated during the operation of motor driven electro-mechanical devices is very audible to the human ear because the characteristics are much different from those of other noises. While such sounds may cause discomfort to the human operator, they may also provide a sense of security, by informing the operator that the device is operating correctly [7, 8]. Therefore, the direction of research on the operation sounds of electro-mechanical devices has differed from that of conventional research on noises. While conventional noise research is solely focused on reducing noises, research on the operation sounds of electro-mechanical devices has focused on enhancing the sound quality in order to provide the sound desired by operators from electro-mechanical devices [9-14]. Research on sound quality began by quantifying subjective elements such as the expectations for devices or preference for certain sounds. There have been efforts to objectively quantify subjective evaluations of various devices.

In numerous case studies, sound quality of electro-mechanical devices used in automotive systems has been investigated experimentally [1-6, 11-17]. A few have examined the sound quality problems in electro-mechanical devices such as power seat adjusters and power window regulators [13,14, 36, 37]. Of these publications, four investigations deal directly with window lift systems. In the first one, Penfold [13] showed that bandpass loudness corresponding to 300-2500 Hz and motor speed reduction affect sound quality significantly. On the other hand, Zhang and Vertiz [14] concluded that intensity (related loudness and roughness) is the most dominant factor, followed by pitch variation and sharpness. Shadden and Lim [37] studied the effect of variation in complex tones on a preference index derived from the paired comparison test [29-31].

Lim [38] developed his own study to refining correlations between deficiencies in window lift systems and psychoacoustic metrics. Lim has classified window lift sounds to 7 attributes, and found out detection methods of those sounds. And finally, preferred criteria of each sounds was made out. These results are suitable for troubles-shooting and pinpointing consumer preferences, but lack of information needed to define abstract concept of sound quality or preference. A systematic study relating human perception of the sound quality of window lift operation has not been reported publicly.

The sound of electro-mechanical devices can be classified into simple impulsive sound, like door latch sound, and long and complex sound, like window lift sound. In former case, people who listen to the sound have relatively simple and clear standards to evaluate quality of the sound. Because the sound is consisted of very short and simple impulsive sounds. Sound level or sharpness could be expected to be major metric to decide sound quality of those electro-mechanical devices. Even so, it is not easy to develop good psycho-acoustic index model of those electro-mechanical devices. In second chapter, I suggest proper method to measure the sound quality of electro-mechanical devices which generate simple impulsive sound based on a case of car door latch.

It is much more complicated that developing psycho-acoustic index model of electro-mechanical devices which generate long and complex sound. The longer and more complex sound is, the standards to evaluate the sound quality are getting more difficult to find. Even for devices with similar acoustic characteristics, the subjective definitions of the characteristics can vary depending on the situation that they are used for. Hence, an extremely deliberate approach is required. For instance, while vacuum cleaners and air conditioners generate similar sounds, people may assess their sounds by different standards. Vacuum cleaners operate for a short time, so an appropriate volume of sound may have positive implications by suggesting strong suction power. However, air conditioners operate for a long time, so quietness itself can be one of the standards for evaluating the product quality [15-17]. Similarly, the basis for sound quality assessment is highly multi-dimensional and complicated, and there is great difficulty with defining such a basis. However, concretely defining such subjective elements through analysis and study of standards that are applicable to each device is highly valuable as a foundation for sound quality research. This research focused on defining the sound quality of window lift operation and developing an objective mathematical description of the sound quality. The window lift is a device that lifts the window on automobile doors and is considered one of the most fundamental electro-mechanical devices to automobiles. Window lifts are almost universally used and are also installed in many compact vehicles. Window lifts are characterized by frequent use and high audibility because they are located immediately adjacent to the human operator within the limited space of the vehicle cavity.

CHAPTER 2

DEVELOPMENT OF PSYCHO-ACOUSTIC INDEX OF SIMPLE IMPULSIVE SOUND: BASED ON A CASE OF CAR DOOR LATCH

2.1 Introduction

In this session, primary purpose of research was to develop psycho-acoustic index of car door latch sound which represent electro-mechanical devices generating simple impulsive sound. It could be expected that sound quality of simple impulsive sound has a characteristic that is determined in its loudness, sharpness or time-length, and also perceived sound of door latch can be rated by simple standards. Therefore I have chosen very simple method to develop psycho-acoustic index of door latch and wanted to confirm the reliability of developed indices.

2.2 Analysis of operating sound of the door latch

As shown in figure 2.1, the sound of a door latch while operating consists of an ‘impact sound,’ which is the main sound; and ‘residue sound,’ which is generated by the motion of the gear moving back to its original position. Both sounds are impulsive sounds that vanish after a short duration and excite a wide frequency range. The interval between the sounds, which is different according to the model of the door latch, is generally from 0.2 sec to 0.5 sec.

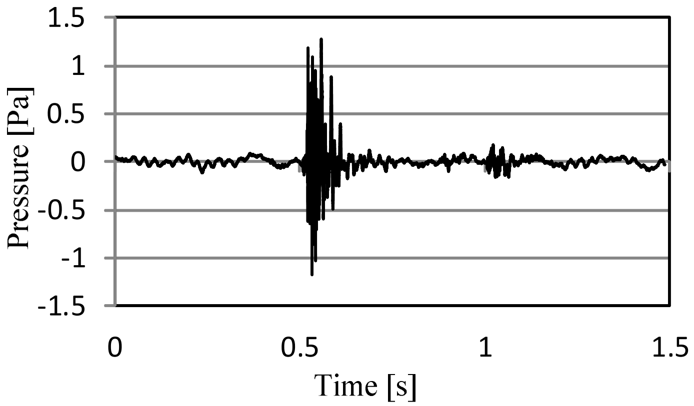


Figure 2.1 – Operating sound of Door Latch

Operating of the door latch is separated into a ‘locking’ motion and ‘unlocking’ motion. Each operating sound could be discriminated by hearing. In this research, the jury test and analysis of the sound was conducted separately by ‘locking’ motion and ‘unlocking’ motion to discriminate the correlation and difference between the two operating sounds. Figure 2.2 and 2.3 show the characteristics of the different motion of the same model. The interval of the impact sound and residue sound, and frequency range when the impact sound is generated are the main differences that stick out.

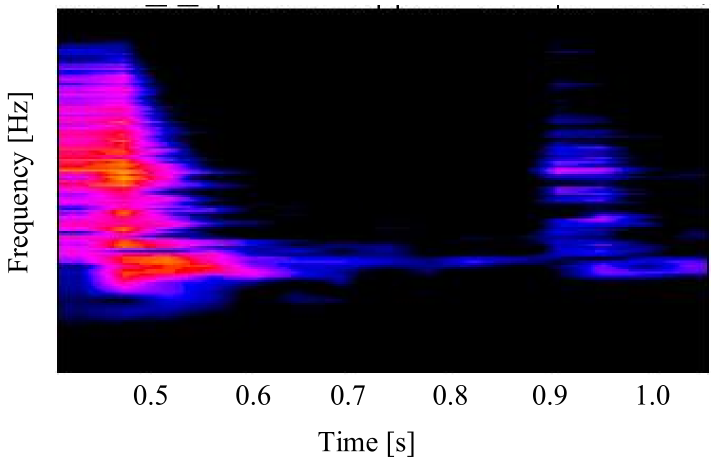


Figure 2.2 – Time-frequency property of ‘Locking’ sound

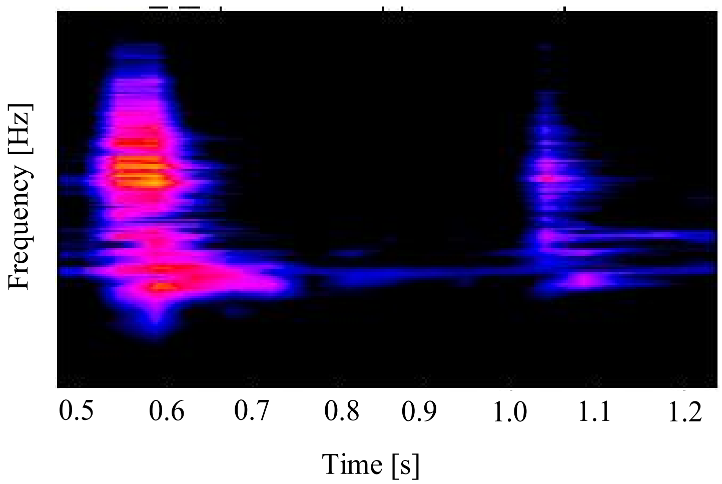


Figure 2.3 – Time-frequency property of ‘Unlocking’ sound

2.3 Subjective preference by jury evaluation

2.3.1 Recording methods

This study was conducted with the door latch. The sound samples that were used in this study were obtained by recording the door latch directly in a real car put in an anechoic chamber. The samples were recorded under the condition of an idle engine state by a man sitting down on a car sheet and wearing headset microphones (BHS II, Head Acoustics). The weight of the man was 72 kg. The headset microphones' range of frequency response was 20 Hz-20 kHz, and the maximum SPL 130 dB. I used headset microphones because I could consider the binaural characteristics of human ears with them. For accurate objective analysis, I recorded the sound samples 5 times for each car. Among them the finest one, which had no abnormal sounds, was used for the jury test.

2.3.2 Method of jury evaluation

The rating method was used to investigate the subjective preferences. The rating method is the process the jurors use to give a score to each sample independently after listening to sounds of the samples. The rating method could achieve higher reliability than other more novice which easily lose their concentration because it is easy to evaluate and takes a short time [21, 33]. The evaluation was conducted in anechoic chamber, and sample sounds were played by PEQ V as shown in figure 2.4.

Figure 2.4 – Jury evaluation using playback equipment

Before the jury evaluations, every jurors get an education to help judge. Jurors had listened to various door latch sounds which were not used for jury evaluation, and rated scores of them. When the responses of each juror showed consistency, jury evaluation was conducted. Figure 2.5 is test sheet, which was used in jury evaluation in this research. Jurors only evaluate by sounds without knowing the models of cars and they provide a score ranging from '0 to 10.' Also, jurors give the reason for the score and comments are used as subjective characteristic data analysis.

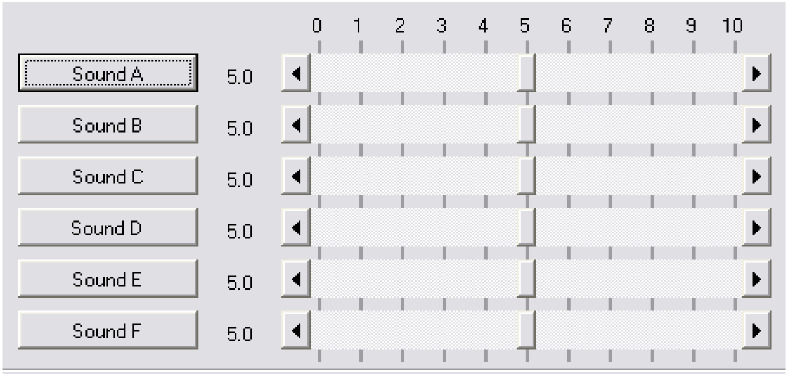


Figure 2.5 – Test sheet used for jury evaluation

A total of 8 cars were used in the jury test, which includes a variety of engine displacement and company. 16 samples, which were 8 opening motions and 8 closing motions, were used because the sounds of the opening motion and closing motion are different.

2.3.3 Results of the jury evaluation

Figures 2.6 and 7 present results of the jury evaluation of the closing motion and opening motion of each door latch. As expected, the standard deviations were small, and the results of jury evaluation was quite clear. Also the results of two operating sound are very similar. Car 5, which took 1st place in both the closing and opening motion, has the smallest engine displacement; and Car 6&7, which had a lower score, had quite a large engine displacement.

Therefore, the preference of the door latch operating sound and engine displacement did not have large correlation.

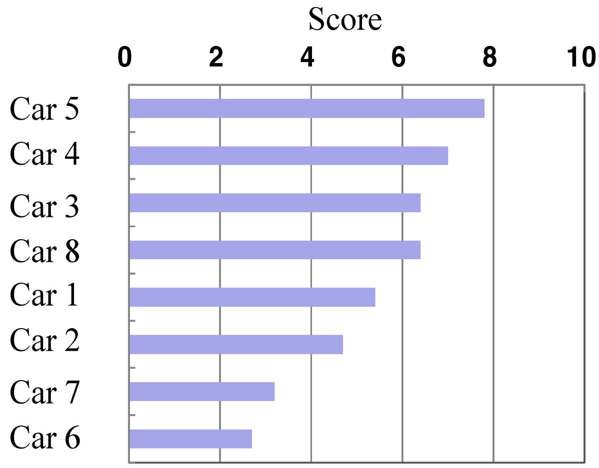


Figure 2.6 – Result of jury testing using ‘Locking’ sound

Figure 2.7 – Result of jury testing using ‘Unlocking’ sound

Figure 2.8 is the preference correlation between the locking sound and unlocking sound. As shown in the figure, there are meaningful correlations between the two sounds, which show different characteristics in sound properties.

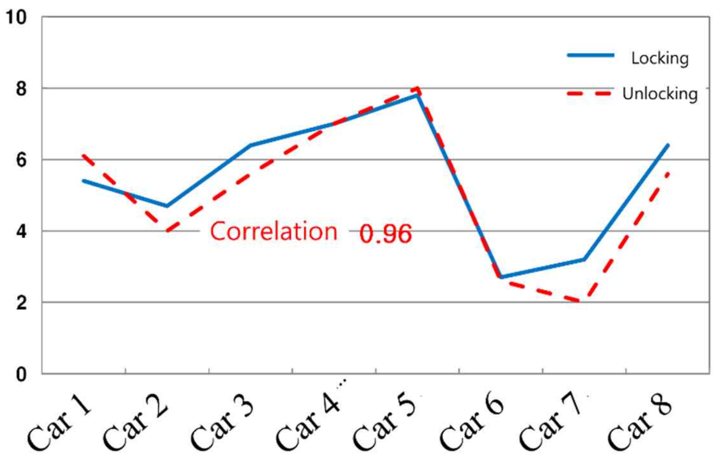


Figure 2.8 – Preference correlation between ‘Locking’ sound (red, solid) and ‘Unlocking’ sound (blue, dash)

2.4 Psycho-acoustic index development of door latch

2.4.1 Objective metrics

To develop the psycho-acoustic index, it was necessary to analyze the correlation between the subjective preference and objective characteristics of the sound. The objective metrics used in this analysis are shown in Table 2.1 and were selected by the comments of the jurors when conducting the jury evaluation. Ln(n:1~5) is loudness related metrics of sound of the door latch. And S_m(m:1~9) & T_l (l:1~4) are sharpness related metrics and time related metrics of sound of the door latch, respectively.

Table 2.1 – Selected objective metrics based on the results of interviews

Subjective expressions	Engineering expression	No. of selected metrics
'Quiet', 'Too loud', 'Noisy', etc.	Loudness related(L)	5
'Too high frequency', 'light sound like toy', 'luxurious sound of bass', etc.	Sharpness related(S)	9
'Opened smoothly', 'late residue sound', etc.	Time related(T)	4

Most of the jurors considered the level of the operating sound a problem when asked about which ones make the operating sound feel luxurious. Roughly, jurors disliked and did not feel luxurious about a very loud sound. Jurors considered the tone of the sound more important than the level of the sound. Below a certain level of sound a problem does not occur; however, the tone of the sound while opening or closing the door is related to the reliability of the product. Also, jurors commented on frequency related words like disliked high frequency sounds or prefers low frequency magnificent sounds. Apart from these comments, some jurors felt inconvenient about the long interval between the impact sound and residue sound.

Metrics influence the luxuriousness of the operating sound and were chosen based on the comment of the jurors. The level and sharpness of the sound, and time-related metrics are expected to be prime metrics. A total of 18 metrics were included: 5 level-related metrics, 9 sharpness-related metrics and 4 time-related metrics.

2.4.2 Sound quality assessment index for the door latch

We conducted regression analysis using the metrics selected through the jury test and found the most well-explainable equations. Equations 1 & 2 are a sound quality assessment index of 'locking' and 'unlocking' sounds, respectively. Both equations have L1 and S6 as important main metrics. As shown in the equations, the quieter and less sharp the sound the higher the score it gets.

$$SQI_{Lock} = 27.15 - 0.23\, L_1 - 6.60\, S_6 \quad (1)$$

$$SQI_{Unlock} = 23.68 - 0.16\, L_1 - 8.10\, S_6 \qquad (2)$$

Table 2.2 & 2.3 are standardized contributions of each metric. According to the results, S6 is a more important metric than L1. This means that the sound quality of the door latch is affected by sharpness more than loudness. Simply speaking, lowering the frequency is a more effective way to improve the sound quality of the door latch than reducing sound level.

Table 2.2 – Regression statistics of SQI of door latch 'Locking' sound

	SE Coeff.	P-value	R-sq(adj)
SQI		0.003	90.8 %
L_1	0.03	0.005	
S_6	3.93	0.15	

Table 2.3 – Regression statistics of SQI of door latch 'Unlocking' sound

	SE Coeff.	P-value	R-sq(adj)
SQI		0.002	94.6 %
L_1	0.05	0.02	
S_6	4.39	0.12	

2.4.3 Sound quality improvement of door latch

Sound field visualization was implemented using acoustic camera to identify the noise source in a condition of real car. For experimental convenience, visualization was done by installing whole door module to selfmanufactured zig. MEMS microphone type 30 channel, spiral array caemra was used for sound field visualization.

Figure 2.9 shows the sound field of the instant moment that door latch operates. Bolting point of door latch and nobe were found to be prime noise source. Impact sound of door latch is direct radiation noise rather than structural-borne noise because main noise is occuring at the point of impact happens.

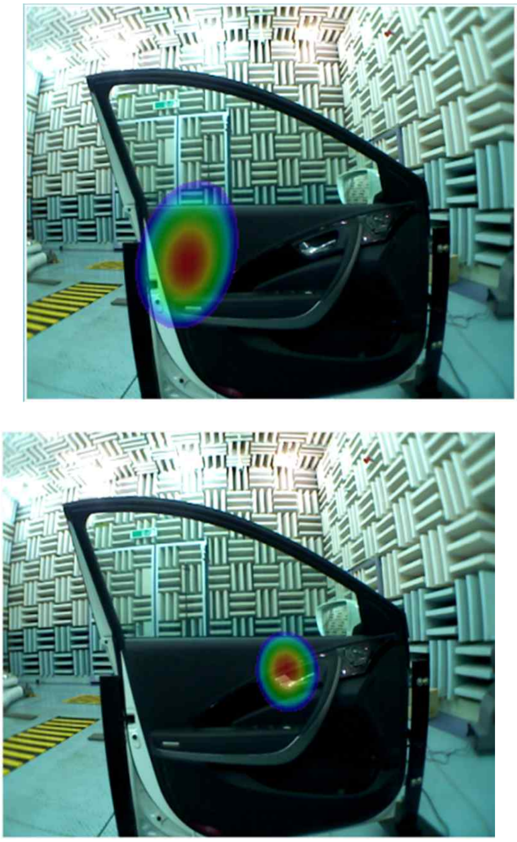


Figure 2.9 – Results of sound field visualization of door latch operating moment

We made a conclusion that most efficient way to improve the sound quality of door latch is to reduce the impact sound of assay, especially sharpness of the sound, because operation sound of door latch directly radiates to air. Thus, to reduce the impact sound of door latch, high viscosity grease was applied to inside of door latch. High viscosity grease reduce the impact force at the moment of impact and stiffness of impact area so that excitation frequency range of impact sound would be lower than before. It can make sharpness of operating sound but also loudness.

To verify the effect of sound quality improvement, improved door latch was applied to real car and operation sound was recorded using same method referred earlier. Effect of sound quality improvement was not confirmed by conducting jury evaluation but substituting objective metrics into psycho-acoustic index. It is coincide to purpose of research which is simplification of sound quality evaluation.

Table 2.4 shows the main sound quality metrics and psycho-acoustic index results of improved door latch's 'opening' motion and 'closing' motion operation sound. For the case of 'closing' motion, L1 reduced degree of 6.2 and S6 reduced degree of 0.11. Because of reduction of L1 and S6, psycho-acoustic index was increased degree of 2.15 which is quite large in a total scale of 10. For the case of 'opening' motion, L1 reduced degree of 4.7 and S6 reduced degree of 0.06. Psycho-acoustic index was increased degree of 1.26 which is not large as ‘closing’ motion but it could also evaluated to be outstanding development.

Table 2.4 – Sound measurement results of optimized door latch in ‘Locking’ sound

	Before optimizing	After optimizing
L_1	83.4	77.2
S_6	1.00	0.89
SQI	1.36	3.51

2.5 Summary

The door latch’s operating sound was evaluated using rating methods, and the results of jury evaluation were analyzed by using linear regression. Psycho-acoustic index developed in this thesis show very high correlation coefficient, it is consisted of reasonable metrics. And also, even though the ‘locking’ and ‘unlocking’ sounds of a door latch have little bit different characteristics, some degree correlations were found in terms of customers’ preferences. For both locking and unlocking sounds within a door latch module, it is found that the smaller and less sharper the sound, the more luxury the quality. Also, it is found that the sharpness of the sound plays a bigger role in deciding the quality of the door latch operating sound. Through this results, it could be confirmed that jury evaluation using rating methods and simple linear regression are enough to analyze simple impulsive sound of electro-mechanical devices. In addition, it is confirmed that the door latch sound is mostly emitted by air-borne noise, which directly radiates to the receiver. Thus, reducing the amplitude of the latch is primarily tackled rather than optimizing the path, and the index that was developed in this study was used to assess the sound quality improvement of the optimized door latch.

CHAPTER 3

DEVELOPMENT OF PSYCHO-ACOUSTIC INDEX OF COMPLEX SOUND: BASED ON A CASE OF WINDOW LIFT

3.1 Introduction

In this chapter, I wanted to study the way to develop psycho-acoustic index of electro-mechanical devices generating long and complex operating sound. For that, window lift which have been used most commonly, and generate operating sound consisted of impulsive sound, tonal sound, broadband sound, etc.. The study was focused on a window lift module, it refers to the assembly comprising the window lift components installed on the door of an automobile, as shown in Figure 3.1. The reason why window lifts were considered in modular form is in order to reduce the effect of the vehicle cavity.

Figure 3.1 Example of the window lift modules used to record the samples

3.2 Methodology

3.2.1 Sound of Window Lift Modules

Window lifts perform the task of lifting and lowering the window glass by using a motor located at the center of the plate. In this study, the operation of a window lift was separated into “ascent” and “descent” because the lifting and lowering of the window glass require different amounts of torque from the motor. Samples were recorded by using a B&K type 4189-A-021 microphone and HEAD SQuadriga at the position coinciding with the location of the ears of the operator assumed to be in the driver's seat. Six different types of window lift modules WLn (n = 1, 2, …, 6) were used in this study. Each model is installed in various types of automobiles, including compact vehicles, sedans, and SUVs. While the detailed characteristics of each model and their operation differ, Figure 3.2 shows the representative characteristics of the sound of window lift operation module.

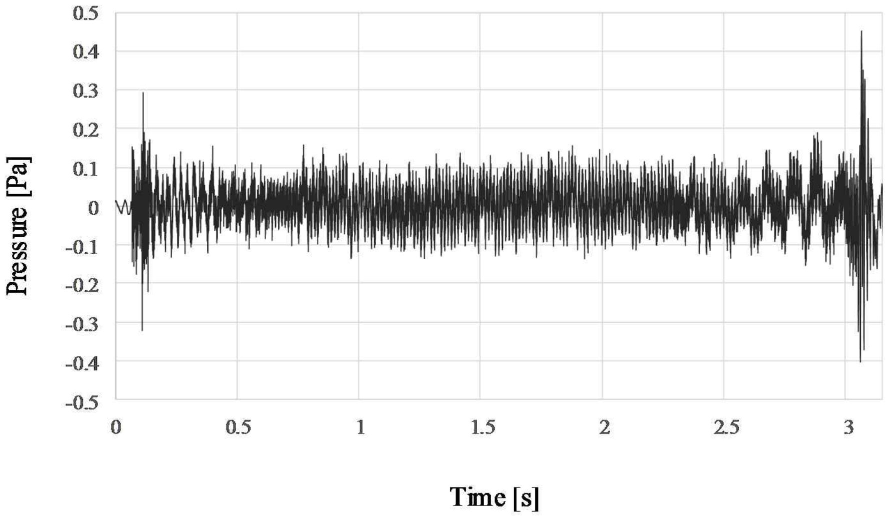


Figure 3.2(a) Typical sound characteristics of a window lift operation: Sound pressure of the window lift operation sound with time

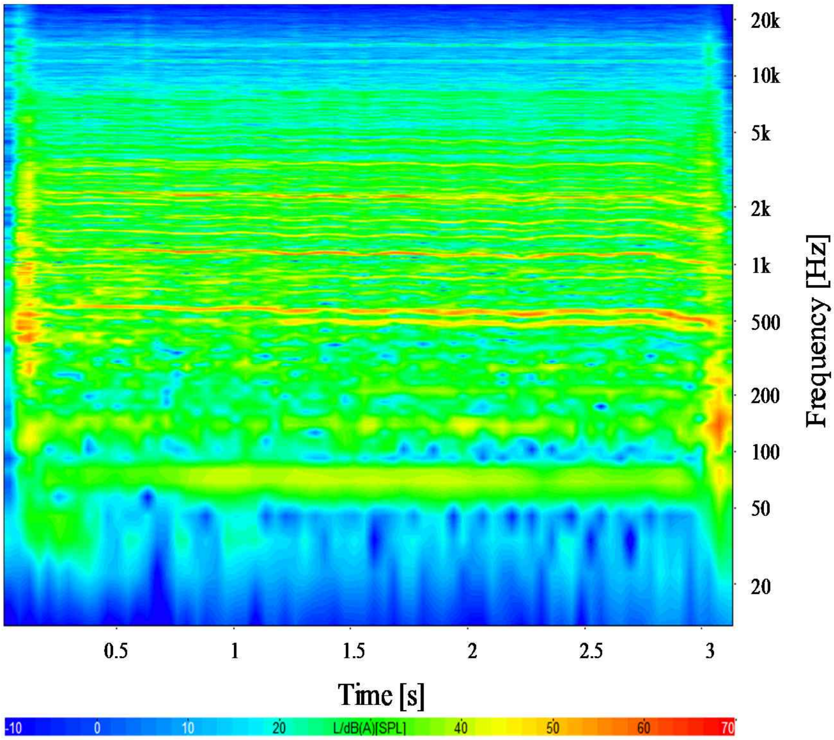
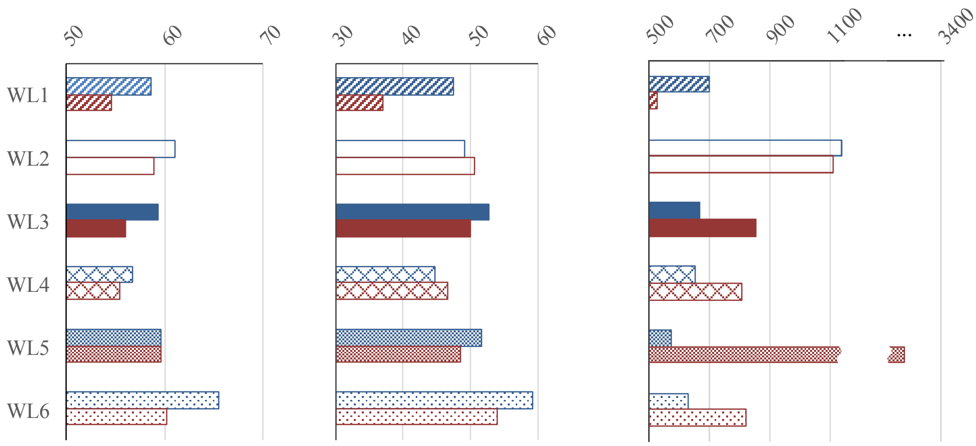


Figure 3.2(b) Typical sound characteristics of a window lift operation: waterfall diagram of the window lift operation sound in the frequency–time domain

Figure 3.2(a) shows a graph of the sound pressure with time. The sound of window lift operation consists of the impact sounds at the start and end points and the moving sound during the 2–3 s of movement of the window glass. Figure 3.2(b) shows a waterfall diagram describing the fast Fourier transform (FFT) of the sound with time from which the difference between the impact and moving sounds can be observed more clearly. The impact sounds at the start and end points excite a broad band of frequencies during a short period time. Meanwhile, the moving sound occurs with friction sound having a small amplitude and a few dominant tonal sounds for which the frequency and amplitude vary with time. Such tonal sounds are mainly generated from the motor, and their frequency can vary with the speed or gear ratio of the motor. DC motors, which are mainly used in window lifts, can be expected to have a significant role in the sound quality of window lifts in terms of tonal sounds because of their particular weakness with regard to noise [18-20].

In order to observe the representative characteristics and differences of the samples used in this study, the overall sound pressure level (SPL) of moving sound of window lift operation excluding the impact sound, SPL of the tones, and frequency of the tones were considered, as shown in Figure 3.3. The overall SPL (Figure 3.3(a)) ranged from 55 dBA to 60 dBA. In addition, all samples except WL5 exhibited a greater operation sound during ascent (blue) than during descent. However, the difference was around 2–3 dBA in smaller cases and 5–6 dBA in larger cases. The magnitude of the tonal sounds (Figure 3.3(b)), which is as important as the overall SPL, is more complicated. The magnitude of the tonal sounds during ascent was found to be greater than that during descent in some cases (WL1, WL3, WL5, WL6) and smaller in other cases (WL2, WL4). The differences in magnitude also varied. The difference between the samples was observed more clearly when the frequency of such tonal sounds was examined (Figure 3.3(c)). The main tonal sounds were never identical for ascent and descent, and it is unlikely that there was a certain tendency for each sample, even when the operating principle of window lift is considered. While this may be considered a weakness in that six samples were used for this study, a reliable jury evaluation can be developed by considering the various characteristics of the operation sounds of each sample.



(a) (b) (c)

Figure 3.3 Basic information on the sounds of the samples used in this study: (a) overall SPLs of the ascent (blue, upper) and descent (red, lower) operation sounds (b) major tone levels of the ascent (blue, upper) and descent (red, lower) operation sounds, and (c) major tone frequencies of the ascent (blue, upper) and descent (red, lower) operation sounds

3.2.2 Jury evaluation

The ultimate objective of this study was to determine which window lift sound people prefer. However, as noted previously, window lift operation produces a complex sound comprising various types of sound, and people can have different preferences with regard to these sounds. In this study, a jury evaluation was administered in order to quantify such complicated evaluation standards based on a semantic differential method using various adjective pairs that are commonly used in the industry to assess the sound quality of window lift operation. A semantic differential method evaluates emotions and is mainly used to quantify ambiguous and complex evaluation standards, such as that for the sound of window lift operation. It was believed to be the most suitable method for this study[21, 22, 33]. Table 3.1 presents the response sheet used for the assessment. The response sheet consists of adjective pairs that can be used to describe the strength of a sound (e.g., “weak–strong” and “acute–grave”), stability of the sound (e.g., “shaking–uniform” and “uncomfortable–comfortable”), and luxuriousness of the sound (e.g., “cheap–luxurious” and “rough–soft”). Evaluating all adjective pairs used for the actual development of window lifts should lead to a detailed analysis of the correlations between similar adjective pairs or the development of a standard for overall preferences.

Table 3.1 Adjective-based response sheet for the jury evaluation based on the semantic differential method

Adjectives	Scale										Antonyms
	1	2	3	4	5	6	7	8	9	10	
frivolous											courteous
weak											strong
loud											silent
acute											grave
rough											soft
shaking											uniform
cheap											luxurious
light											heavy
uncomfortable											comfortable
preference											

A total of 76 jurors participated in the jury evaluation. All of the jurors were experts who are involved with the development of window lifts. The jury evaluation was conducted by playing a sample recorded previously through Head BHS II. There were a total of 12 samples: six of an ascent sound and six of a descent sound. The samples were separated into an ascent sound group and descent sound group during the jury evaluation. This was because the loads on the motor during the lifting and lowering of the window glass are different, and it was believed that this difference is not described by certain rules for each model. The samples were treated under blind test conditions during the evaluation to prevent all prior knowledge regarding the model.

3.2.3 Factor Analysis

Factor analysis is a technique for reducing multiple observed variables into a few major factors based on the correlations between each variable[23, 24]. In this study, the variables were the nine adjective pairs used in the previous jury evaluation, excluding the preference. These variables were analyzed by using principal component analysis (PCA) through varimax rotation. The factors were selected to be those with eigenvalues exceeding 1. The intention of this analysis was to define the sound quality of window lifts, which was assessed by using abstract adjective pairs up to this point, by using a few mutually orthogonal factors.

3.2.4 Objective metrics used for analyzing results

SPL is the most commonly used quantity for sound evaluation. However, SPL does not accurately represent the amplitude of the sound that is actually perceived by people [21, 25]. Moreover, people do not evaluate a sound purely based on the amplitude. Thus, various attempts have been made to develop psycho-acoustical metrics that can serve as standards for sound quality assessment. This study also aimed to discover the correlation between metrics using subjective impressions and other metrics developed empirically. Various metrics other than those presented below were calculated, and the correlations were analyzed.

3.2.4.1 Tonality

Tonality is a psycho-acoustical metric that represents the ratio between tone to noise within the entire signal [21, 26, 27]. In this study, values for the tonality of the sounds of window lift operation were obtained by using two tonality calculation schemes: DIN 45681 and the Aures method.

Table 3.2 Penalties assigned to the calculation of tonal sound components based on the level difference

Level difference	Penalty
> 12 dB	6 dB
> 9 dB	5 dB
> 6 dB	4 dB
> 4 dB	3 dB
> 2 dB	2 dB
> 1 dB	1 dB
≤ 1 dB	0 dB

The DIN 45681 standard defines the tonal component contained within a narrowband spectrum. The difference between the tonal and background noise levels is analyzed, and the masking effect is also considered. As indicated in Table 3.2, a penalty value between 0 and 6 dB is determined by using the maximum difference between the tonal and background noise components, and the tonal component is calculated by using this penalty value26.

The calculation based on works by Terhardt and Aures is achieved via short time spectra arrived at via the FFT of 4096 points and a Hanning window. The first pass searches for spectral lines Si that are larger than both their respective neighbors Si±1. Only lines that are at least 7 dB larger than the lines Si±2 and Si±3 are considered. The seven-line groups with the indexes i - 3 to i + 3 found in this manner as pure tones are removed from the spectrum. Only up to a single tonal component per critical band is considered. A search is then performed for narrowband noise in the remaining spectrum of bandwidths smaller than the critical bandwidth at this location. This is because such signals also create an impression of tonality, although only to a small extent27.

3.2.4.2 Loudness

Loudness is a psycho-acoustical metric developed to objectively represent the subjective perception of the amplitude of a sound because SPL does not accurately reflect the amplitude of a sound perceived by human [21, 28]. Loudness was developed to consider both the intensity and duration of a sound and the characteristics of an auditory system with respect to different frequencies. In this study, quantities relating to the amplitude of the window lift operation sounds were calculated by referring to the ISO 532 standard. According to this standard, loudness can be calculated as follows28:

$$N' = 0.08\left(\frac{E_{TQ}}{E_0}\right)^{0.23}\left[\left(0.5 + 0.5\frac{E}{E_{TQ}}\right)^{0.23} - 1\right] \tag{1}$$

where N' is the specific loudness in sone/Bark, E is the excitation of the sound, and E_{TQ} and E_0 are the excitation values under the conditions of quiet ambient and a reference sound with an intensity of $I_0 = 10^{-12}\ \mathrm{W/m^2}$, respectively. The total loudness of a sound is given by

$$N = \int_0^{24\ \mathrm{Bark}} N'dz \tag{2}$$

where N is the total loudness of the sound and z is the critical band rate in Bark.

3.2.4.3 Modulation

Modulation is a psycho-acoustical metric that objectively quantifies the degree of fluctuation in a sound. There are two types of sound modulation: amplitude modulation and frequency modulation. Both types of modulation occur in window lift operation sound. Hence, it was necessary to analyze both types in this study.

The sound pressure $p_0(t)$ of a sound for which the amplitude modulates around $\hat{p}_{carrier}$ can be expressed as follows:

$$p_0(t) = \hat{p}_{carrier} \cdot (1 + m \cdot \sin(2\pi f_{mod} \cdot t)) \cdot \sin(2\pi f_{carrier} \cdot t) \qquad (3)$$

Where, f_{mod} is the modulation frequency, $f_{carrier}$ is the carrier frequency, and m is the modulation depth. Among these quantities, the degree of amplitude modulation was calculated by using m in this study [21, 30].

More complicated calculations are required if the carrier frequency of the sound itself is modulated [21, 30-32]. In this study, such calculation was based on the frequency modulation of the maximum-level tone among the components of the window lift operation sound. The rate of change in frequency of the maximum-level tone, amplitude of the change, mean, variance, and kurtosis were examined.

3.3 Results and discussion

3.3.1 Semantic Differential Analysis

While appropriate instructions were provided to the jurors prior to the test, outliers in the responses obtained from the jury evaluation needed to be removed. Outliers that deviated from the mean interval were removed and analyzed, as shown in Figure 3.4. On average, 73.83 responses out of 76 total responses were used from each set; the standard deviation was 4.15 [21, 22, 33, 34].

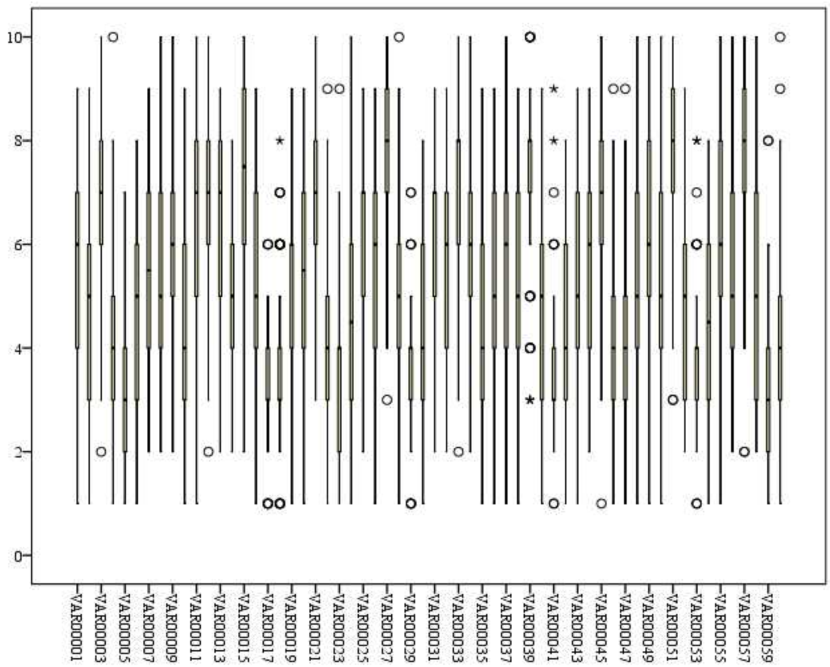
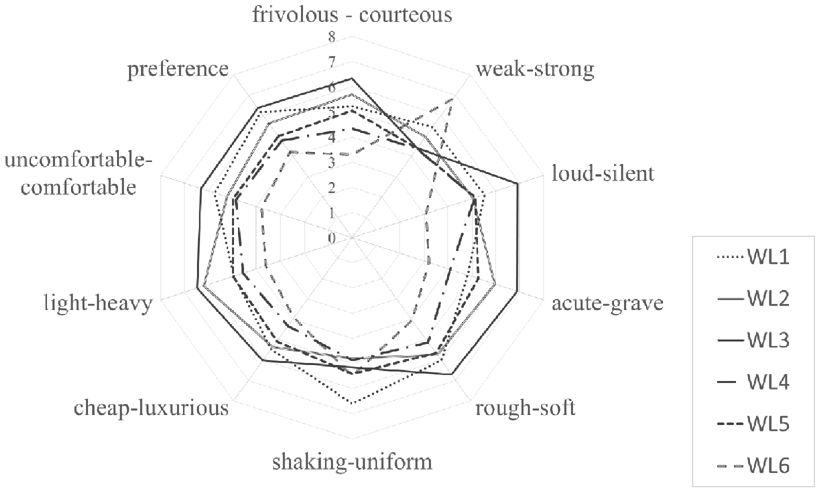
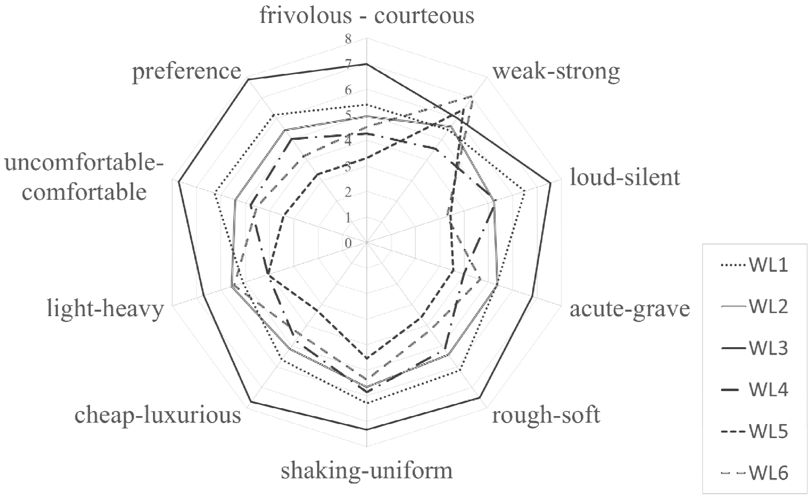


Figure 3.4 Box plot of all responses

Figure 3.5 shows the subjective analysis results for each model. Figure 3.5(a) shows the semantic differential distribution for ascent. WL3, which had the highest preference score, scored the highest for all adjective pairs except "weak–strong" and "shaking–uniform." WL3 also scored the highest in preference for descent (Figure 3.5(b)). However, unlike for the ascent operation, it also scored the highest in preference for “shaking–uniform”. There was a need to analyze whether “shaking–uniform” occupies different roles in the ascent and descent operations and what the reason is if so. WL6, which had the lowest score in preference for the ascent operation, had the highest score for “weak–strong.” WL6 exhibited similar tendencies in both ascent and descent operations. Thus, it can be deduced that the sense of strength has a negative influence on preferences for the sound of window lift operations. The broad classification of adjective pairs established during the preparation stage, such as strength, stability, and luxuriousness, may have implied different meanings for the jurors, and the standard for classification may have also been ambiguous. Factor analysis was performed to examine this in more detail.



(a)



(b)

Figure 3.5 Results of the jury evaluation based on the semantic differential method: (a) ascent (b) descent

3.3.2 Results of Factor Analysis

Based on the previous jury evaluation, each sample was evaluated in terms of the subjective impressions of the adjective pairs. Based on these results, the correlations between adjective pairs that were used to evaluate the sound of window lift operations to this point and the contributions of each were examined through factor analysis23, 24. Table 3.3 presents a correlation matrix in which the correlations between each adjective pair and each factor can be observed. High correlations between adjective pairs that convey the heaviness of the sounds (e.g., "frivolous–courteous," "acute–grave," and "light–heavy") were hypothesized, and the correlation coefficients were observed to be extremely high in reality. However, while the adjective pairs "uncomfortable–comfortable" and "loud–silent" were predicted to form separate sets, these were found to actually be highly correlated to "frivolous–courteous" and "acute–grave." Moreover, the adjective pairs "rough-soft" and "shaking-uniform," which were predicted to form separate sets, showed different characteristics during ascent and descent operations. For ascent, both adjective pairs showed high correlations to "frivolous–courteous" and "acute–grave" and belonged to the mainstream set. For descent, however, "shaking–uniform" showed low correlations to the other adjective pairs, appearing to be independent. Moreover, "weak-strong" shows low correlations to other adjective pairs for both operations, exhibiting independent behavior.

Table 3.3 Correlation between adjective pairs and factors obtained from factor analysis: (a) ascent and (b) descent

(a)

Adjective pairs	Factors	
	1	2
frivolous–courteous	0.982	-0.125
weak–strong	-0.681	0.503
loud–silent	0.952	-0.089
acute–grave	0.936	-0.242
rough–soft	0.997	0.024
shaking–uniform	0.049	0.986
cheap–luxurious	0.980	0.106
light–heavy	0.905	-0.314
uncomfortable–comfortable	0.979	0.099

(b)

Adjective pairs	Factors	
	1	2
frivolous–courteous	0.999	-0.015
weak–strong	-0.065	0.984
loud–silent	0.864	-0.477
acute–grave	0.985	0.107
rough–soft	0.951	-0.307
shaking–uniform	0.949	-0.258
cheap–luxurious	0.988	-0.124
light–heavy	0.9	0.401
uncomfortable–comfortable	0.985	-0.158

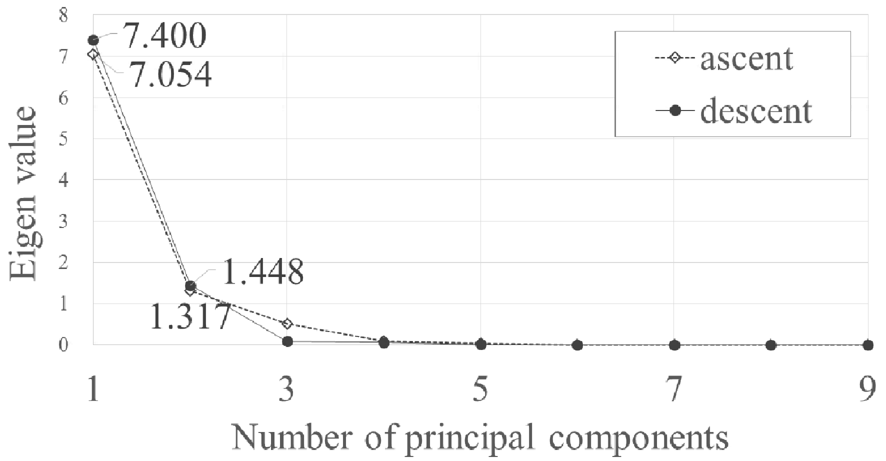
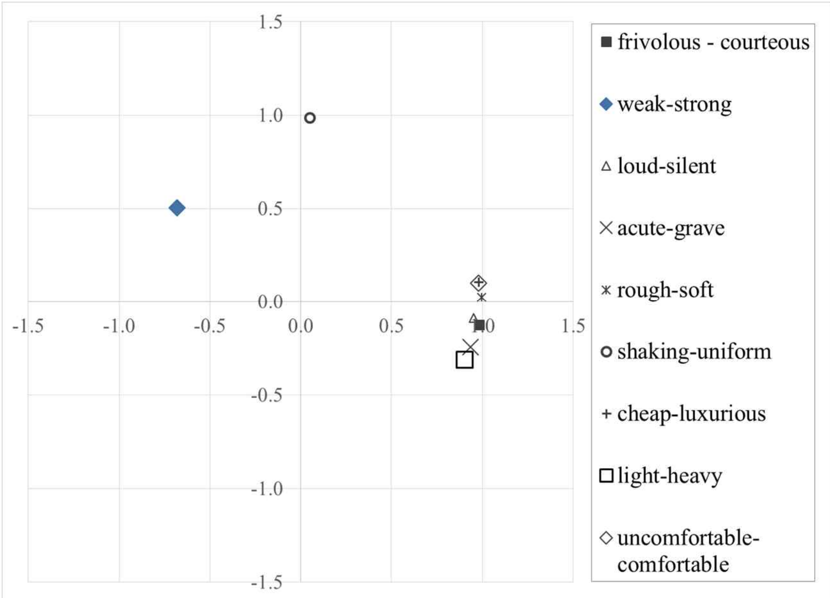
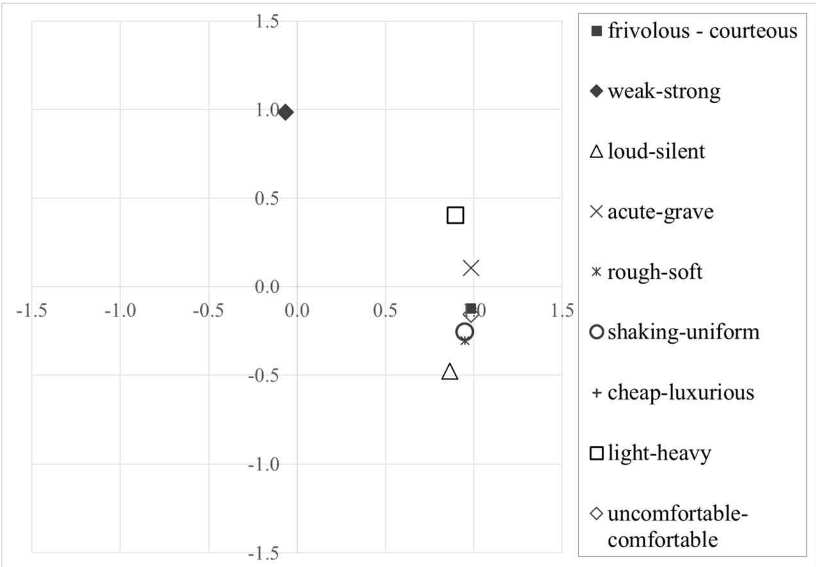


Figure 3.6 Scree plot of the eigenvalues for the factors obtained from the factor analysis: (a) ascent (dotted lines, open circles) and (b) descent (solid lines, solid circles)

Figure 3.6 shows a scree plot that describes the eigenvalues of the factors obtained from the factor analysis. For both the ascent and descent operations, there were two factors with eigenvalues greater than 1. Moreover, Cronbach's α between factors 1 and 2 was 0.00 for both the ascent and descent operations. Cronbach's α was used to determine the correlation between variables; values greater than 0.7 indicate a high correlation between two variables34. Therefore, Cronbach's α of 0.00 between factors 1 and 2 implies that the factor analysis successfully separated the original variables into uncorrelated variables. The eigenvalues of factor 1 were 7.054 and 7.400 for the ascent and descent operations, respectively. These were more than fivefold greater than the eigenvalues of factor 2, which were 1.317 and 1.448, respectively. This indicates that two principal factors are required to explain the entire group of adjective pairs and that factor 1 had the greatest significance. If this is represented in terms of percentage variance, the percentage variances of factors 1 and 2 were 78.38% and 14.63%, respectively, for the ascent operation and 82.22% and 16.09%, respectively, for the descent operation. Thus, 93.01% and 98.31% of the adjective group for the ascent and descent operations, respectively, can be explained by using these two factors only.



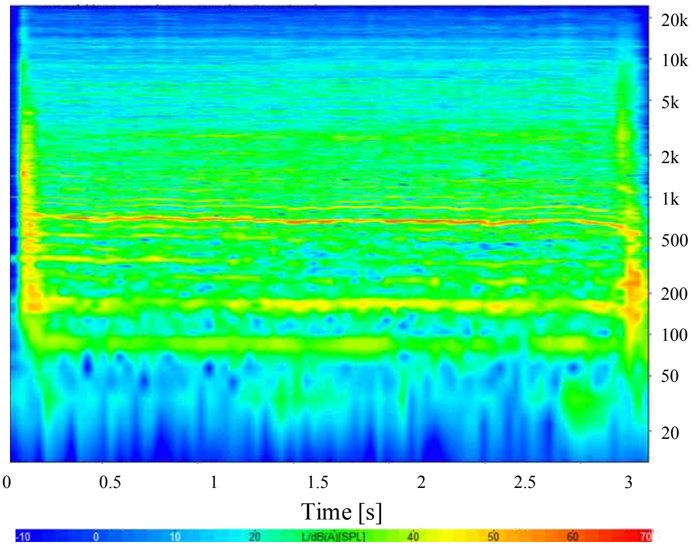
(a)



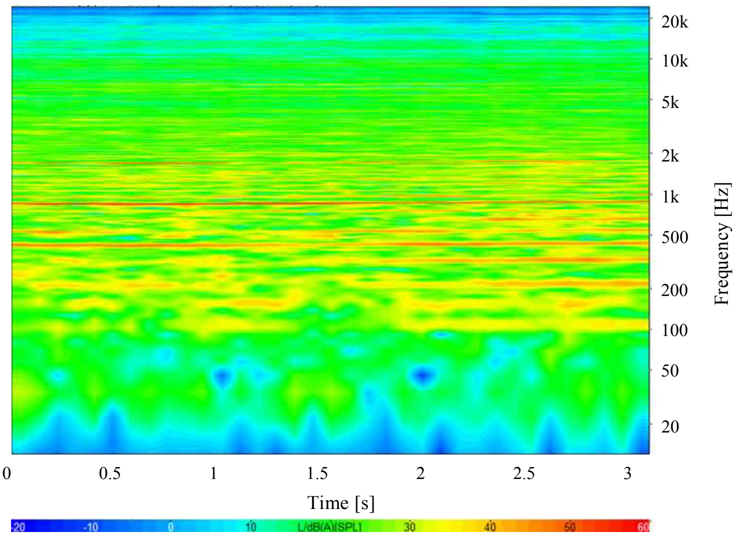
(b)

Figure 3.7 Component diagram of the rotated space: (a) ascent and (b) descent

Figure 3.7 shows the component diagram of the rotated space, and Table 3.3 shows the component matrix obtained from the factor analysis. For the ascent operation, most adjective pairs were strongly correlated to factor 1 (F_{ascent} 1), while "shaking–uniform" and "weak–strong" were correlated to factor 2 (F_{ascent} 2). The representative elements of the sets of adjective pairs correlated to factors 1 and 2 may be defined as "luxuriousness" and "uniformity," respectively. Meanwhile, the descent operation exhibited a difference from the ascent operation. While there was no difference between the overall trends, "shaking–uniform" was included in the factor 1 set (F_{descent} 1), and only "weak–strong" showed a high correlation to factor 2 (F_{descent} 2). The representative elements of factors 1 and 2 for the descent operation can be defined as "luxuriousness" and "strength," respectively. The difference in factor 2 between the ascent and descent operations can be attributed to the difference in operating principles.



(a)



(b)

Figure 3.8 FFT characteristics of the operation sound of WL3 with time:

(a) ascent and (b) descent

Figure 3.8 shows the frequency characteristics of the sounds for ascent (Figure 3.8(a)) and descent (Figure 3.8(b)) operations over time. Because the ascent operation lifts the window glass upward and imposes a greater load on the motor, the tonal sound generated by the motor was greater than that of the descent operation. Moreover, in contrast to the absence of modulation of the tonal sound of the descent operation, the sound of the ascent operation was modulated from 640 Hz to 680 Hz. This is because the speed or torque of the motor differs as the magnitude of the load imposed on the motor varies with the extent of curvature of the window glass. The difference is audibly distinguishable. It can be deduced that “shaking–uniform,” which appeared to be a major component of the factors for the ascent operation occupied a similar role to that of the other adjective pairs for the descent operation owing to such a difference in sound.

3.3.3 Correlation Analysis

The final objective of this study was to develop a psycho-acoustic index that can objectively represent the sound quality of window lift operations. For this purpose, correlation equations between the sound quality and principal factors were obtained through correlation analysis between the preference for operation sounds previously obtained from the jury evaluation and the factors obtained from the factor analysis. Correlation equations between the factors and psycho-acoustical metrics were derived through a correlation analysis. Finally, a psycho-acoustic index that can explain the sound quality of window lift operations using objective quantities was developed through synthesis of the derived correlation equations. Linear regression was used to analyze the correlation between each variable. Linear regression is an analysis technique that expresses a dependent variable y in terms of the linear combination of various independent variables x_n as presented in Eqn. (4)35, 36:

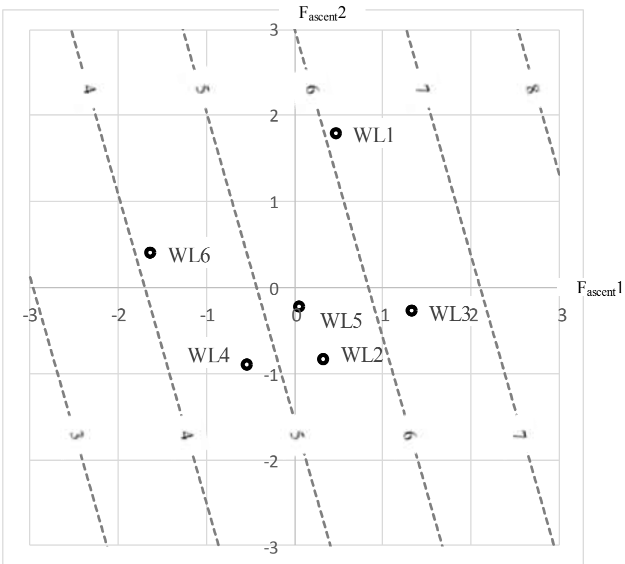
$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \cdots + \beta_n x_n \tag{4}$$

3.3.3.1 Embodying the concept of preference

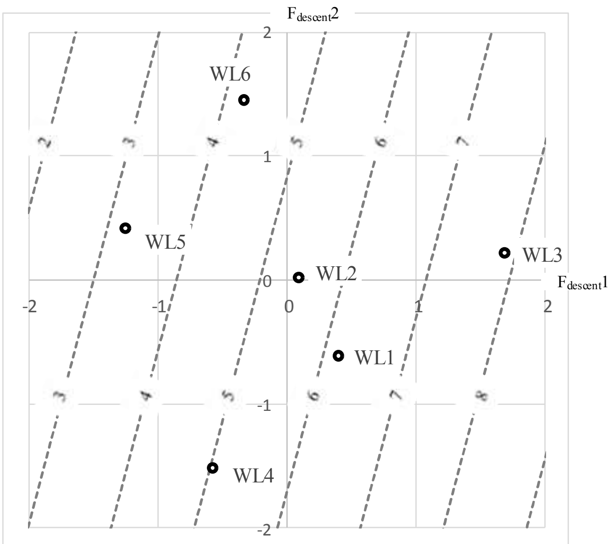
First, the correlation between the preference for operation sounds and the principal factors was analyzed. This was used to define the preference for operation sounds, which has been addressed in an abstract manner, in a more rational and concrete manner. Equation (5) describes the correlation between the preference for operation sounds and the two principal factors. Table 3.3 presents the statistical quantities regarding each variable.

$$preferenc \quad e_{ascent} = 5.345 + 0.792 \times F_{\mathrm{ascent}}\ 1 + 0.220 \times F_{\mathrm{ascent}}\ 2 \tag{5}$$

The R^2 and R^2_{adjust} values for Eqn. (5) were 94.76% and 91.26%, respectively, which indicates high reliability. The P-values for each variable were 0.006 and 0.144 for $F_{\mathrm{ascent}}\ 1$ and $F_{\mathrm{ascent}}\ 2$, respectively. Equation (5) indicates that the sound preference for the ascent operation has a positive correlation to $F_{\mathrm{ascent}}\ 1$, which is related to "luxuriousness," and $F_{\mathrm{ascent}}\ 2$, which is related to "uniformity." This may mean that people prefer more luxurious and uniform ascent operation sounds. In addition, the difference in coefficients may imply that "luxuriousness" has more influence on determining the preference between the two factors. Such a relationship must be understood for research on enhancing window lift operation sounds because it can be used to develop an effective and efficient enhancement strategy. Figure 9(a) represents Eqn. (5) on the factor plane. The line corresponding to scores of 3–8 in sound quality preference is marked with a dotted line, and the six samples used for evaluation are shown in terms of the actual values of the factors for each sample. WL1 and WL3 obtained identical scores of 6 in preference. WL3 was more luxurious than WL1 but less uniform, while WL1 was less luxurious than WL3 but more uniform. Figure 9(a) shows that it is more effective to research methods for producing luxurious sounds than for producing uniform sounds in order to design a window lift with a pleasant ascent operation sound.



(a)



(b)

Fig. 3.9 Values of factors (dots) for each sample on the factor plane and correlation lines (dashed) between preferences and factors: (a) ascent and (b) descent

A similar process was also applied to the descent operation sound, and the resulting correlation equation between the subjective preferences and factors is given below:

$$preference_{\mathrm{descent}} = 5.335 + 1.552 \times F_{\mathrm{descent}}\ 1 - 0.395 \times F_{\mathrm{descent}}\ 2 \tag{6}$$

The R^2 and R^2_{adjust} values for Eqn. (6) were 99.93% and 99.88%, respectively, which implies high reliability. Moreover, the P-values for each variable were 0.0001 and 0.001 for $F_{\mathrm{descent}}\ 1$ and $F_{\mathrm{descent}}\ 2$, respectively. The preference for the descent operation sounds showed a positive correlation to $F_{\mathrm{descent}}\ 1$, which represents “luxuriousness,” and a negative correlation to $F_{\mathrm{descent}}\ 2$, which represents “strength.” It can be deduced that people prefer luxurious but not strong sounds when the window glass is lowered. Moreover, the coefficients show that “luxuriousness” has more influence on determining the preference between the two factors and that the difference is greater than the difference in contribution between the two factors for the ascent operation. Figure 3.9(b) represents Eqn. (6) on the factor plane. WL3 obtained a preference score of around 8; WL3 was more luxurious than WL1 but less strength and had a near-average value for $F_{\mathrm{descent}}\ 2$ but a high value for $F_{\mathrm{descent}}\ 1$. Furthermore, WL4 and WL6 did not show a significant difference in terms of overall preference because they had similar values of $F_{\text{descent}}\ 1$ despite the significant difference in $F_{\text{descent}}\ 2$.

3.3.3.2 Psycho-acoustic index

Based on the previous factor analysis result, the independence between the two factors was established from Cronbach's α of 0 for both the ascent and descent operations. Therefore, if Eqns. (5) and (6) are synthesized with correlation equations that explain each factor in terms of objective sound quality metrics, a psycho-acoustic index for window lifts can finally be established as desired. The correlation equations that determined the values of the factors from sound quality metrics were also based on linear regression, and the sound quality metrics used for this correlation analysis can be classified as related to loudness, acuteness, roughness, and modulation. These metrics were selected based on the results of interviews conducted with the jurors during the jury evaluation.

The first factor for the ascent operation $F_{\text{ascent}}\ 1$ can be defined as "luxuriousness" and was expected to require loudness, tonality, and roughness to be explained. A correlation analysis was performed with various metrics and the result is given below:

$$\mathrm{F}_{\text{ascent}}\ 1 = 11.44 - 0.237 \times \mathrm{Tonality}_{\mathrm{D,max}} - 0.175 \times E_{high} \qquad (7)$$

where $\mathrm{Tonality}_{\mathrm{D,max}}$ denotes the maximum value of tonality during the operation as calculated with DIN 45681 and E_{high} denotes the sound energy belonging to the 3150–10,000 Hz band. The R^2 and R^2_{adjust} values for Eqn. (7) were 98.59% and 97.65%, respectively. Moreover, the P-values for each variable were 0.003 and 0.019 for $\text{Tonality}_{D,max}$ and E_{high}, respectively. Both variables were within reliable intervals of significance and were highly correlated to F_{ascent} 1. Based on these results, people can be deduced to judge if the sound of the window lift operation is luxurious based on the amplitude of the tonal sound component and magnitude of the high-frequency broadband sound energy. A sound without much tonal sound component, which may trigger annoyance, or high-frequency component, which is responsible for the sense of roughness, can be considered luxurious.

The second factor for the ascent operation F_{ascent} 2 can be defined as uniformity and was expected to be related to the modulation and strength of the sound. The result of the correlation analysis given shown below:

$$\mathrm{F}_{ascent}\ 2 = 29.93 - 0.0475 \times m_{max} - 0.392 \times E_{bw} \qquad (8)$$

where m_{max} denotes the degree of modulation and E_{bw} denotes the sound energy in the 50–200 Hz band. The R^2 and R^2_{adjust} values for Eqn. (8) were 94.04% and 90.06%, respectively. Moreover, the P-values for each variable were 0.034 and 0.007 for m_{max} and E_{bw}, respectively. Both variables were within a reliable range of significance and were highly correlated to $F_{ascent}2$. According to Eqn. (8), people prefer a sound to be more uniform and clear with less amplitude modulation and fewer low-frequency components.

Synthesizing Eqn. (5) with Eqns. (7) and (8) obtains

$$SQI_{\text{ascent}} = 20.990 - 0.188 \times \text{Tonality}_{\text{D,max}} - 0.139 \times E_{high} - 0.010 \times m_{\text{max}} - 0.086 \times E_{bw} \quad (9)$$

The sound quality of an ascent operation for a window lift can be assessed in terms of four objective metrics with Eqn. (9). Without additional jury evaluations, large amounts of time and cost can be conserved through the use of Eqn. (9), and the possibility of errors due to uncertainty in the experimental method of a jury evaluation can be excluded.

The first factor for descent $F_{\text{descent}}\ 1$ can also be defined as "luxuriousness," similar to that for ascent. Therefore, the main focus was on whether it can be explained in terms of identical variables to $\text{F}_{\text{ascent}}\ 1$, and it was hypothesized that the reliability of Eqn. (7) would also be high if such were possible. The correlation equation between $\text{F}_{\text{descent}}\ 1$ and sound quality metrics is given below:

$$\text{F}_{\text{descent}}\ 1 = 16.35 - 2.127 \times \text{Tonality}_{\text{A,max}} - 0.265 \times E_{high} \quad (10)$$

where $\text{Tonality}_{\text{A,max}}$ denotes the maximum value of tonality during operation as calculated with the Aures model, and E_{high} denotes the sound energy in the 3150–10,000 Hz band. The R^2 and R^2_{adjust} values for Eqn. (10) were 97.90% and 96.50%, respectively. Moreover, the P-values for each variable were 0.074 and 0.003 for $\text{Tonality}_{\text{A,max}}$ and E_{high}, respectively. An interesting aspect is that, while the sound quality metrics that explain $\mathrm{F_{descent}\ 1}$ were tonality and high-frequency sound energy, which are identical to $\mathrm{F_{ascent}\ 1}$ from a broader perspective, the tonality for $\mathrm{F_{descent}\ 1}$ was calculated according to the Aures model, unlike $\mathrm{F_{ascent}\ 1}$. While the proportion of tonal sound occupies a significant role in determining the human perception of luxuriousness, both $\mathrm{Tonality_{D,max}}$ and $\mathrm{Tonality_{A,max}}$ can be viewed as unreliable in terms of accurately reflecting the proportion of tonal sound as perceived by people. While correlation equations with high reliability were developed for both $\mathrm{F_{ascent}\ 1}$ and $\mathrm{F_{descent}\ 1}$, additional research appears to be necessary regarding the tonality metrics.

The second factor for descent operation $\mathrm{F_{descent}\ 2}$ can be defined in terms of "strength" and was expected to be explained by the loudness and roughness of the sound. The result of the correlation analysis is given below:

$$\mathrm{F_{descent}\ 2} = -16.72 + 0.261 \times E_{bw} \tag{11}$$

The R^2 and R^2_{adjust} values for Eqn. (11) were 87.49% and 84.36%, respectively. Moreover, the P-value for E_{bw} was 0.006. The single variable used to explain $F_{\mathrm{descent}}\ 2$ was the low-frequency sound energy, which was also used to explain $F_{\mathrm{ascent}}\ 2$. From the previous factor analysis, while the adjective pair "weak–strong" belongs to both $F_{\mathrm{ascent}}\ 2$ and $F_{\mathrm{descent}}\ 2$, the adjective pair "shaking–uniform" only belongs to $F_{\mathrm{ascent}}\ 2$ due to the difference in operating mechanisms. Such a tendency can be confirmed once again by comparing Eqns. (8) and (11). In terms of equations, $m_{\max}$ and E_{bw} roughly represent the perceptions of “shaking–uniform” and “weak–strong,” respectively.

Similar to the ascent operation, the psycho-acoustic index for the descent operation was developed by synthesizing Eqn. (6) with Eqns. (10) and (11):

$$SQI_{\text{descent}} = 37.299 - 3.300 \times \text{Tonality}_{\text{A,max}} - 0.4113 \times E_{high} - 0.103 \times E_{bw} \qquad (12)$$

With this equation, the sound quality for the descent operation of a window lift can be assessed based on three objective metrics only without additional jury evaluations. However, while Eqns. (9) and (12) are the same in that the responsible metrics are the tonality, E_{high}, and E_{bw} and that these are negatively correlated, there is a slight difference in the extent. Modulation of the sound, which was the most distinct difference between the ascent and descent operation sounds, also led to a difference in terms of objective sound quality metrics. This metric was $m_{\max}$, which represents the amplitude modulation of the sound.

3.4 Verification of model

Six different types of sound samples, VSn (n = 1, 2, …, 6) were used in verification test. Three types of samples were obtained by recording from window lift modules, and additional three samples were created by conducting signal modification. Signal modifications were done to ensure diversity of psycho-acoustical characteristics of samples.

Simple rating method were used to conduct jury evaluation, because I already have found out the concepts of "human perception of the sound quality of window lift operation" and just needed to confirm verification of developed sound quality model. Also, 11 jurors participated in the jury evaluation.

Table 3.4 – Comparison between jury evaluation results and scores calculated by using psycho-acoustic index in ascent

	Jury evaluation results	Psycho-acoustic index scores
VS_1	3.510	3.780
VS_2	4.765	4.270
VS_3	5.988	5.670
VS_4	6.245	5.980
VS_5	5.325	5.720
VS_6	4.091	4.510

Table 3.5 – Comparison between jury evaluation results and scores calculated by using psycho-acoustic index in descent

	Jury evaluation results	Psycho-acoustic index scores
VS_1	4.623	4.782
VS_2	5.234	4.988
VS_3	6.412	6.614
VS_4	6.827	6.511
VS_5	5.776	5.342
VS_6	5.332	5.414

Table 3.4 and 5 are jury evaluation results and scores calculated by using psycho-acoustic index in ascent and descent respectively. Correlation index between two results are 0.929 and 0.942, respectively. In both operation(ascent and descent), two results are highly correlated and these can ensure the reliability of psycho-acoustic index developed in this study.

3.5 Summary

The sounds generated from window lift operation for lifting and lowering are audibly distinguishable. Thus, the analysis and development of an index were performed separately for the ascent and descent operations. First, the results of the jury evaluation were analyzed by using factor analysis in order to quantify the abstract concept of “human perception of the sound quality of window lift operation.” For the ascent operation, jurors evaluated a luxurious and uniform sound to be pleasant. For the descent operation, the sense of strength was observed to be required for a pleasant sound. Subsequently, a psycho-acoustic index was developed through correlation analyses between preferences and factors and between factors and sound quality metrics in order to explain the results more objectively. It was observed that the sound quality of the ascent operation can be assessed according to the tonality, high-frequency sound energy above 3150 Hz, degree of modulation, and low-frequency sound energy below 200 Hz. The sound quality of the descent operation can be assessed according to the tonality, sound energy above 3150 Hz, and low-frequency sound energy below 200 Hz. Considering that these final two equations allow for an objective assessment of the sound quality that is not influenced by the situation the jurors are in or the test environment, the development of these equations can be considered significant. And also verification tests could ensure the reliability of psycho-acoustic index model.

CHAPTER 4

CONCLUSIONS

I have studied objective measurement of perceived sound quality of electro-mechanical devices in vehicles by dividing operating sounds in simple impulsive sound and complex long sound. In chapter 2, procedure to develop the psycho-acoustic index of simple impulsive operating sound was established based on a case of car door latch. Rating method was used for jury evaluation and it was found that using rating method is suitable way to investigate preferences to simple impulsive sound. It costs less time and it is easier to conduct than any other methods. And then, to analyze the results of jury evaluation, linear regression was used, because I expected that simple impulsive sound can be explained simply by its loudness, sharpness or length of time. As I expected, sound quality indices developed by using linear regression showed high correlation coefficient and were consisted of loudness sharpness related metrics. For both locking and unlocking sounds within a door latch module, it is found that the smaller and less sharper the sound, the more luxury the quality. It may be regarded as a natural results. But through these results, it is found that the sharpness of the sound plays a bigger role in deciding the quality of the door latch operating sound, so sharpness of door latch operating sound has to be major subject to improve sound quality of door latch. In addition, it is confirmed how much of sharpness can influence to the sound quality. To confirm the influence of sharpness to sound quality, I also conducted sound source analysis. It is confirmed that the door latch sound is mostly emitted by air-borne noise. Thus, reducing the excitation force of the latch itself is primarily tackled rather than optimizing the path. The index that was developed in this study was used to assess the sound quality improvement of the optimized door latch. Improved door latch was applied to real car and operation sound was recorded using same method referred earlier. The operating sound of improved door latch had lower sharpness and loudness than original door latch's operating sound, and it is confirmed that sound quality were also improved.

In chapter 3, procedure to develop the psycho-acoustic index of long and complex operating sound was established based on a case of window lift. Unlike the simple impulsive sound, long and complex sound is consisted of impulsive sound, tonal sound, broadband sound, etc.. Because of that, people feel confused to evaluate the sound quality of such electro-mechanical devices and have very ambiguous standards. To develop the sound quality of these devices, it is needed to embody the concepts of "human perception of the sound quality of window lift operation." For that, jury evaluations were conducted by using semantic differential method. Then the results of the jury evaluation were analyzed by using factor analysis. For the ascent operation, jurors evaluated a luxurious and uniform sound to be pleasant. For the descent operation, the sense of strength was observed to be required for a pleasant sound. Next, to explain the concepts of "human perception of the sound quality of window lift operation." more objectively, correlation analyses between preferences and factors and between factors and sound quality metrics were conducted. It was observed that the sound quality of the ascent operation can be assessed according to the tonality, high-frequency sound energy above 3150 Hz, degree of modulation, and low-frequency sound energy below 200 Hz. The sound quality of the descent operation can be assessed according to the tonality, sound energy above 3150 Hz, and low-frequency sound energy below 200 Hz. Considering that these final two equations allow for an objective assessment of the sound quality that is not influenced by the situation the jurors are in or the test environment, the development of these equations can be considered significant.

The results of this study may be applicable not only to develop the sound quality indices of electro-mechanical devices but also to help embodying the ambiguous concept of sound quality.

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국 문 초 록

본 논문은 자동차에 설치되는 모터 전장 부품의 음질 연구에 대하여 연구하였다. 모터 전장 부품의 작동음은 크게 짧은 충격음과 여러 가지 다양한 소리로 구성된 복잡한 소리로 나누어 질 수 있다. 충격음은 음질 연구는 도어 랫치를 기반으로, 복잡한 소리는 윈도우 리프트를 기반으로 연구를 실시하였다. 먼저 도어 랫치의 음질을 평가하는 지수를 개발하기 위하여 도어 랫치의 작동음을 잠금과 열림으로 나누어 진행했다. 8개의 도어 랫치 작동음이 연구에 사용되었으며, 그를 이용라여 비전문가를 대상으로 평정법을 사용한 청음평가를 실시하였다. 이를 통해 도어 랫치에 대한 주관적 평가 결과를 확인 할 수 있었다. 또 이 결과를 통하여 객관적 지표들과의 통계적 상관성을 선형회귀분석을 이용해 분석한 결과 loudness와 sharpness가 도어 랫치의 음질을 결정하는데 가장 중요한 인자임을 알 수 있다. 또한 이 때 개발된 음질 평가 지수는 매우 높은 신뢰도를 가졌다. 또한 보다 높은 정확성 확보를 위하여 검증 실험을 실시 하였고, 이를 통해 만들어진 인덱스와 절차에 대한 신뢰도를 높일 수 있었다. 다음으로 윈도우 리프트와 같은 복잡한 작동음을 갖는 부품의 음질 평가 지수를 개발하였다. 본 연구에서 윈도우 리프트 작동음은 “상승”과 “하강”으로 나누어 진행하였다. 앞 서

진행한 충격음과는 달리 윈도우 리프트의 작동음은 그 성질이 복잡한 만큼 사람들의 평가 기준을 정확히 알 수 없다. 그를 정확히 하기 위하여 본 연구에서는 "어의미 분석" 법을 이용하여 청음평가를 실시하였다. 이러한 평가 결과를 이용하여 요인 분석을 진행하였고, 그를 통해 사람들의 작동음 평가 기준을 구체화할 수 있었다. 윈도우 리프트 작동음은 '고급감'과 '균일성', '강도' 로 평가가 가능하였고, 그런 감성을 결정짓는 객관적 인자들은 tonality 와 modulation, band-pass Energy 등이 있다. 후에 개발된 음질 평가 지수를 평가하기 위한 검증 실험 역시 실시하였으며, 이를 통해 연구의 결과와 절차에 대한 적합성을 확인할 수 있었다.

주요어 : 음질, 전장 작동음, 충격음, 도어랫치, 모터작동음, 윈도우 리프트, 어의미 분석, 요인 분석
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