공학석사 학위논문

차량 실내 윈드노이즈 변동감의 음향심리학적 평가 모델 개발

Psychoacoustic Model for Perceived Fluctuation of Vehicle Interior Wind Noise

2018 년 2 월

서울대학교 대학원

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Abstract

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Vehicle interior wind noise (VIWN) generated by aerodynamic flow is one of the major factors affecting the pleasantness in a vehicle passenger compartment, especially in the high-speed condition. In particular, fluctuating wind noise can be perceived as more annoying at a high speed. Therefore, the present study aimed to investigate the characteristics of the fluctuation of VIWN and to develop its psychoacoustic model. In the first experiment, VIWN was considered to consist of a carrier noise (partially weighted pink noise) and various amplitude-modulation components. Subjective evaluation for 25 stimuli was performed by a total of 12 participants; thereafter, modulation strength (MS) was proposed to fully explain the subjectively perceived fluctuation of the VIWN. The results of correlation analysis showed that the MS of octave-band scale were more strongly related to the subjective evaluation of the VIWN fluctuation than loudness or fluctuation strength. In the second experiment, to verify the effectiveness of the MS, 19 stimuli recorded in a wind tunnel were used. The results showed that three parameters (loudness and the MS of 7th and 8th octave bands) were highly correlated with the subjectively perceived fluctuation of VIWN. Based on the results of hierarchical linear regression analysis, it was concluded that the MS of 7th octave (f_c=4000Hz) can fully explain the subjectively perceived fluctuation of VIWN. Therefore, in the present study, the MS of the 7th octave band was determined as the psychoacoustic model for the VIWN fluctuation.

Keyword : Sound quality, Wind noise, Fluctuation strength, Sinusoidal amplitude modulation, Vehicle interior sound

Student Number : 2016-20669

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1. Introduction

With recent advances in vehicle interior noise control technology, the absolute value of the vehicle interior noise has decreased. This noise reduction has led to an increase in user expectations of vehicle interior sound quality. Therefore, a focus on vehicle interior sound quality has been recently suggested to be priority for the improvement of user satisfaction, and a numerous studies seeking to enhance vehicle interior sound quality have been carried out [1,2]. While various sources of noise, such as engine and tire/road contact, contribute to vehicle interior sound [3], the aerodynamic flow around A-pillar is a major cause of severe noise in a vehicle passenger compartment at a high speed. The noise generated by the aerodynamic flow is defined as wind noise. Especially in luxury cars, even if the absolute level of wind noise is low, wind noise can be dominant and very noticeable due to its occurrence near the passengers [4,5]. Therefore, in high-speed conditions, wind noise has a major impact on the pleasantness of vehicle interior sound.

Extensive research has addressed the problem of wind noise control. For instance, Otto and Feng [5] and Hoshino and Katoh [6] emphasized the strong relationship between loudness and subjective assessment of wind noise; more specifically, Otto and Feng [5] demonstrated a strong positive correlation between loudness and annoyance of the perceived wind noise. Meanwhile, the unsteadiness of wind noise caused by obstacles at a high speed has also been extensively studied. For example, Blommer et al. [7] and Lemaitre et al. [8] focused on the time-varying events of wind noise, such as wind buffeting and gusting. Both studies developed evaluation models to describe human perception of wind buffeting or gusting with respect to measurable values. In particular, Lemaitre et al. [8] suggested that fluctuation strength is an important factor to represent human perception of wind buffeting when excluding loudness. While these studies examined the impulsive events, Riegel et al. [9] considered fluctuating wind noises. The authors indicated that the fluctuating wind noise can be perceived as more unpleasant than steady-state noise, and concluded that changes in an incident angle of the aerodynamic flow can lead to modulations in amplitude or frequency.

Furthermore, Zwicker and Fastl [12] proposed that fluctuation strength is a parameter that can explain how fluctuating noises are perceived and evaluated. Specifically, several studies demonstrated that amplitude-modulated noises are perceived as fluctuating at low modulation frequencies up to 20 Hz [10-12]. However, the human perception and subjective assessment of wind noise fluctuation were not quantified yet; similarly, the evaluation model for wind noise fluctuation was not developed. Although the fluctuation strength is strongly related to fluctuations of sound, we should verify whether the human perception of wind noise fluctuation is related to fluctuation strength. Moreover, at a high speed (especially in windy environments), vehicle interior wind noise (VIWN) can severely fluctuate even when there are neither obstacles, nor other vehicles on the road. This fluctuation can lead to a greater annoyance and elicit anxiety in the passengers. Therefore, in order to improve user satisfaction and sense of safety, the fluctuation of VIWN should be controlled.

However, controlling and reducing the fluctuations of VIWN require correlating the results of the subjective evaluation with the results of objective measurements. In other words, the research aiming to evaluate and overcome the fluctuations of the VIWN should quantify the subjective assessment of this fluctuation. Therefore, the present study investigated the characteristics and human perception of the fluctuation of VIWN. The goal of this study was to develop the psychoacoustic model for the fluctuation of VIWN. We conducted two tests designed to determine the correlation between subjective and objective features of fluctuation of VIWN. As broadband noise, such as VIWN, has a very low pitch strength [12], only the amplitude modulation was considered; that is the fluctuating VIWN was considered as sinusoidally amplitude-modulated (SAM) noise. Next, traditional psychoacoustic metrics such as loudness and fluctuation strength of 25 stimuli were first given to determine the relationship between traditional metrics and the fluctuation of VIWN. To this end, a jury test was performed by a total of 12 listeners who were asked to evaluate how fluctuating the stimuli were; by doing so, we obtained the subjective evaluation of the fluctuation of VIWN. To describe the subjectively perceived fluctuation of the VIWN in terms of measurable data, modulation strength (MS) was proposed. Subsequently, a jury test with 7 listeners was performed by using 19 stimuli recorded in a wind tunnel to verify whether the MS could be applied to wind noise real-recorded inside the vehicle. To analyze the results, hierarchical linear regression analysis was carried out for a comparison the effectiveness of objective measurable parameters such as loudness and the MS. According to the results, the MS of seventh octave band (f_c=4000 Hz) was found to be able to represent subjective assessment of the VIWN fluctuation.

2. Psychoacoustic metrics

2.1. Fluctuation strength

Time varying sounds can lead to the perception of fluctuation strength or roughness: fluctuation strength for slowly varying sounds with modulation frequencies between approximately 5 and 20 Hz, and roughness for fast varying sounds with higher modulation frequencies, such as those above 20 Hz. Zwicker and Fastl [10-12] suggested that fluctuation strength has a bandpass characteristic for which the maximum value occurs around a modulation frequency of 4 Hz, and emphasized the necessity to consider temporal masking patterns of noise. The following model of fluctuation strength was proposed (see Eq. (1)):

$$F \sim \Delta L / \left(\frac{f_{mod}}{4\ \text{Hz}} + \frac{4\ \text{Hz}}{f_{\text{mod}}} \right), \tag{1}$$

where F is the fluctuation strength, f_{mod} is the modulation frequency, and ΔL is the depth of the temporal masking pattern. The terms $f_{\text{mod}}/4\ \text{Hz}$ and $4\ \text{Hz}/f_{\text{mod}}$ are related to the merging effect and the memory effect, respectively. Fluctuation strength can be calculated by an approximation of the envelope function of the signal, as modulation generates envelopes of sound waves. Envelope formation indicates the calculation of the magnitude of a complex envelope. While the real part of a complex envelope can be provided by the sound wave itself, the imaginary part should be calculated. Generally, Hilbert transform is used for this calculation. In this study, Artemis 8.0 of HEAD Acoustics was employed to calculate fluctuation strength.

2.2. Loudness

Loudness reflects the human auditory characteristics regarding the perceived amplitude of the sound; it refers to the perception of sound intensity. The unit of loudness is sone, and 1 sone is the amplitude of 40 dB and 1 kHz tone. According to he ISO 532B standard [12-14], specific loudness can be defined as follows (see Eq. (2)):

$$N'=0.08\left(\frac{E_{TQ}}{E_0}\right)^{0.23}\left[\left(0.5+0.5\frac{E}{E_{TQ}}\right)^{0.23}-1\right], \tag{2}$$

where N' is the specific loudness in sone/Bark, E_{TQ} is the excitation of sound at under the a quiet condition, and E_0 is the excitation of the reference sound whose intensity can be calculated using Eq. (3).

$$I_0=10^{-12}\ \mathrm{W/m^2}. \tag{3}$$

The total loudness can be calculated by summarizing specific loudness using Eq. (4).

$$N=\int_0^{24\ \mathrm{Bark}} N'\,\mathrm{d}z, \tag{4}$$

where N is the total loudness of the sound and z is the critical band rate in Bark. Since this study attempted to consider the fluctuating VIWN, disregarding the transient and impulsive events such as wind buffeting, the loudness values of all the stimuli were calculated based on ISO 532B. To reflect the cabin acoustic characteristics of a vehicle passenger compartment, a diffuse field condition was applied.

3. Fluctuation of VIWN: Sinusoidal amplitude-modulation

3.1. Stimuli and conditions

A quantification of the subjective characteristics of VIWN requires computing the correlation of subjective and objective features of VIWN fluctuation. Since wind noise is broadband noise, pitch strength is much fainter than pure-tone noise. Therefore, modulation in frequency was not considered in the present, and the fluctuating VIWN was treated as a SAM noise. SAM noise can be defined as shown in Eq. (5) [15]:

$$s(t)\text{=A}[1+m\cos(2\pi f_{\mathrm{m}}t)]n(t), \tag{5}$$

where $n(t)$ is a carrier noise, A is a scaling factor, m is the modulation depth, and f_{m} is the modulation frequency. According to the frequency spectrum of the VIWN [9, see Figure 5], $n(t)$ was determined as a partially weighted pink noise (N = 90 dB SPL) in this study. When the modulation frequencies are higher than 20 Hz, roughness rather than fluctuation strength is generated [11]. Thus, the seven modulation frequencies in harmonic that are lower than 20 Hz (0.25, 0.5, 1, 2, 4, 8, 16 Hz) were employed. If the two modulating waveforms are added to the carrier noise, SAM noise can be defined as shown in Eq. (6) [16]:

$$s(t)\text{=A}[1+m_1\cos(2\pi f_{m_1})+m_2\cos(2\pi f_{m_2})]. \tag{6}$$

Moreover, en various modulating components are added to the carrier noise, it can be expanded as shown in Eq. (7):

$$s(t)=\mathrm{A}[1+m_{\mathrm{t}}\cos 2\pi f_{\mathrm{t}}+\sum_{\mathrm{i}=1}^{\mathrm{N}} m_{\mathrm{i}}\cos 2\pi f_{\mathrm{i}}], \quad (7)$$

where f_{t} is 4 Hz, m_{t} is the modulation depth of f_{t}, and m_{i} is that of the i-th modulation frequency (f_{i}=0.25, 0.5, 1, 2, 8, 16 Hz). For a broadband noise carrier, the threshold for amplitude modulation detection is m=0.05 (typically -25 dB SPL) [17]; therefore, the five cases of the modulation depth (m_{t}=0.05, 0.08, 0.11, 0.13, 0.17) were considered. Since, as stated by Zwicker and Fastl [10-12], fluctuation strength has a bandpass characteristic with the maximum value near the modulation rate of 4 Hz, in the present study, we considered the five cases of a ratio between the m_{t} and m_{i} (m_{t}: m_{i} = 1:0, 1:1, 1:0.5, 1:0.25, 1:0.125, 1:0. which means that only the modulating component of 4 Hz is added to the carrier noise and m_{i} is zero). Subsequently, with the five cases of the modulation depth and the five cases of the ratio, 25 stimuli were obtained.

3.2. Procedure

A total of 12 students (24-31 years of age; 1 female, 11 male) participated in this experiment. All participants were experienced listeners who had participated in psycho-acoustical experiments in our laboratory at least once 3 months before. All subjects had pure-tone thresholds within our laboratory norms.

Subjective assessment of the fluctuation of VIWN was obtained with a two-alternative forced-choice (2AFC) method [18]. The 25 stimuli were randomly paired and the participants were asked to listen to 300 pairs of signals and choose a more fluctuating one. Each trial consisted of two 5 s observation intervals separated for 500 ms. The experiment was conducted in a semi-anechoic room (cut-off frequency

= 80 Hz, the background noise is 16 dBA). The participants chose one of two stimuli by using an evaluation tool developed in our laboratory and a PEQ-V of HEAD Acoustics. After completing evaluations of 100 signals all participants were allowed to rest for at most 20 minutes.

3.3. Results

Fig. 3.1 shows the results of subjective assessment of fluctuation of stimuli. The relationship between the subjective evaluation and modulation depth, m_t is described for five cases of depth ratio. The abscissa is the modulation depth of 4 Hz, m_t, and the ordinate is a subjective assessment of how fluctuating the vehicle inside wind noise is. The larger number of subjective assessment represents that the subjects perceived more fluctuation in the noise. The five lines indicate the five cases of the ratios between the modulation depth of 4 Hz (m_t) and that of the other frequencies (m_i); 1:0 (squares, dashed line), 1:0.125 (circles), 1:0.25 (triangles), 1:0.5 (diamonds), and 1:1 (squares), respectively. It can be seen that an increase in modulation depths led to an increase in the subjectively perceived fluctuations of all cases of ratios, i.e., VIWNs with the larger modulation depth were perceived as more fluctuating noises. These results are consistent with the dependencies of fluctuation strength on tmodulation depth proposed by Zwicker and Fastl [12]. Moreover, for all cases of the modulation depth of 4 Hz (m_t), the ratio 1:1 was perceived as the most fluctuating noise. This suggests that the VIWN is perceived as more fluctuating if various modulating components with large values of modulation depth are applied.

3.3.1. Correlation analysis between the results of subjective assessment and objective characteristics

In order to determine the relationship between the subjective assessments and the objective features of stimuli, measurable parameters, such as psychoacoustic metrics, were obtained to represent the objective features of stimuli; fluctuation strength and loudness were employed in the present study. Since we aimed to verify whether fluctuation strength would be related to the fluctuations of VIWN, the fluctuation strength of all stimuli for jury test was considered. As discussed in the introduction, loudness has an important effect on wind noise quality; therefore, loudness was also considered. Fluctuation strength and loudness of all stimuli were calculated based on Artemis 8.0 of HEAD Acoustics (see Table 3.1 for the results of metrics calculations). As can be seen in Table 3.1, the loudness values of stimuli were relatively consistent, as only one carrier noise for stimuli was used. Subsequently, correlation analysis was conducted to identify the relationship between the subjective and objective characteristics. As can be seen in Table 3.2, the Pearson correlation coefficient between the results of the subjective assessments and the fluctuation strength was 0.575 ($p < 0.01$), suggesting that the fluctuation strength has an impact on the subjective evaluation of the fluctuation of the VIWN. However, this Pearson correlation coefficient does not necessarily indicate a strong relationship; if we derive a regression equation, at most 33 percent of the variance in subjectively perceived fluctuation of VIWN can be accounted for by fluctuation strength. Therefore, the subjectively perceived fluctuations of the VIWN cannot be fully explained by fluctuation strength. Moreover, as shown in Table 3.2, the Pearson correlation coefficient between loudness and the results of subjective evaluation was 0.460. This value is not sufficient to confirm a strong relationship either; therefore, it can be concluded that it is difficult to fully describe the subjectively perceived fluctuations of VIWN by loudness or fluctuation strength. Accordingly, more specific parameter should be introduced to clarify the relationship between the subjective and objective features of the VIWN fluctuation.

3.3.2. Modulation strength (MS)

Although the fluctuation strength is conventionally considered to be the most general and accurate psychoacoustic metric for calculating the fluctuation in noises [10-12], the VIWN fluctuation is not fully explained by fluctuation strength. The term “sound quality” is related to the suitability of a product with respect to specific pre-set requirements [19], i.e., users evaluate the sound quality based on their expectations. Thus, a psychoacoustic model focusing only on VIWN should be investigated to describe and predict the fluctuation in this noise. To this end, in the present study, we proposed a new model, MS, to quantify the subjectively perceived fluctuations of VIWN with respect to measurable data. That is, we developed MS as a psychoacoustic model_specific for VIWN.

The results of subjective evaluation showed that the modulation depth is related to fluctuations of VIWN for all cases of depth ratio, and the case of ratio 1:1 was perceived as the most fluctuating wind noise for all cases of modulation depth. Therefore, we considered all modulation frequencies as not adopting frequency weighting, i.e., the band-pass characteristics where the modulation frequency of 4

Hz generates the maximum value of the fluctuation strength [10, see Figure 1] were ignored. For modulation frequencies above 20 Hz, other sound impression such as roughness are perceived and, then, temporal changes are no longer detected [11,12]. Since our goal was to develop a psychoacoustic model for the fluctuation, not roughness, of VIWN, the modulation frequencies below 20 Hz were considered. Fig. 3.2 presents a schematic flow diagram illustrating the calculation procedure of the MS. VIWNs that include fluctuating components are filtered by a band-pass filter, so that one can focus on the frequency range of interest. Subsequently, sinusoidal amplitude modulations are detected by the Hilbert transform, and all the modulation depths in dB scale are summed up for the modulation frequencies below 20 Hz. This value is defined as the MS. In the present study, in order to determine the frequency range closely related to the subjective assessment of the VIWN fluctuation, octave scale band-pass filters were used. Since wind noise generally occurs at frequencies of 500 Hz and above [6], 5 types of octave scale band-pass filters (range of f_c=500 Hz to f_c=8000 Hz, i.e., 4th to 8th octave band) were employed. For each octave band, MSs are shown in Table 3.3.

Furthermore, correlation analysis was conducted to verify the accuracy of the MS. Table 3.4 shows Pearson correlation coefficients between the MS value of each band and the results of subjective evaluation. As shown in Table 3.4, the MS of 7th and 8th octave bands are highly correlated with the subjectively perceived fluctuation of VIWN; therefore, fluctuations in the frequency range from 2800 to 11200 Hz can significantly influence subjective assessments. Fig. 3.3 is a scatter plot of the results of subjective evaluation against the MS. Fig. 3.3(a)-(b) shows the strong relationship between the subjectively perceived fluctuation of VIWN and the MS of 7th and 8th octave bands. By contrast, fluctuation strength in the 7th and 8th octave bands showed less correlation with the results of subjective evaluation (see Fig. 3.4). Therefore, it can be concluded that the MS is more effective to describe the subjective evaluation of the fluctuation in VIWN than fluctuation strength; in addition, the MS of 7th and 8th octave bands are particularly significantly correlated with the subjective assessment. However, because all stimuli in this experiment were made using the identical carrier noise and applying artificial modulating components, it should be examined whether the MS can be applied for recorded sounds in a vehicle passenger compartment. Moreover, as mentioned in the introductory section, loudness has a major impact on the subjective evaluation of vehicle interior sound quality and, therefore, the effectiveness of the MS should be verified for stimuli with various loudness values. Thus, the validity of the MS of 7th and 8th octave bands for real-recorded stimuli inside the vehicle has to be examined.

4. Verification of MS

4.1. Stimuli and conditions

In Part 3, subjective evaluation and several parameters (loudness, fluctuation strength, the MS of 7th, 8th octave bands) were obtained for artificial wind noises, and the MS of 7th, 8th octave bands showed a significant correlation with the results of subjective evaluation. The artificial wind noises were created using the partially weighted pink noise with various sinusoidally amplitude-modulating components. However, as discussed in Section 3.3.2, the validity of the MS of 7th and 8th octave bands should be tested for real-recorded VIWN. In order to verify whether subjective perception of the fluctuation of real-recorded VIWN correlates with the MS of 7th and 8th octave bands, interior sounds of six vehicles were recorded in a full-scale ¾ open wind tunnel (nozzle area 28 m^2). A rotating belt was installed between the wheels and a boundary layer suction system was used to model the moving ground so that to simulate real road conditions. Six types of vehicles were positioned along the axis of the air flow in which three types of speed conditions (105, 120, and 140 kph) were simulated. In order to exclude other noise sources, such as the engine or tire/road contact, recordings were obtained inside the vehicles with engine off and windows closed in a semi-anechoic room (cut-off frequency=80 Hz, the background noise = 54 dBA at 100 kph). Two microphones (B&K 4189) were used to consider the binaural auditory system. As the incident angle of the aerodynamic flow can cause the VIWN fluctuation [9], four types of yaw angle conditions (see Fig. 4.1) were considered. Among these 72 stimuli, the samples that were difficult to distinguish were excluded, and several samples were amplified to make loudness variation in the stimuli. A final selection of 19 stimuli was then used for subjective evaluation.

4.2. Procedure

A total of seven students (24-31 years of age; 1 female, 6 male) participated in this experiment; all participants also did the previous test described in Section 3.2. 2AFC method was adopted for subjective assessment of the fluctuation of VIWN [18]. 19 stimuli were randomly paired, and therefore, participants were asked to listen to 171 pairs of signals and choose more fluctuating one in a semi-anechoic room (cut-off frequency = 80 Hz, the background noise is 16 dBA). Each trial consisted of two 5 s observation intervals separated for 500 ms. The evaluation tool developed in our laboratory and a PEQ-V of HEAD Acoustics were used; on completion of evaluations of 100 signals, all participants were allowed to rest for at most 20 minutes.

The MS of 7th and 8th octave bands were calculated based on the procedure illustrated in Fig. 3.2. Fluctuation strength and loudness were also calculated based on Artemis 8.0 of HEAD Acoustics. The results are summarized in Table 4.1.

4.3. Results

Correlation analysis was conducted to verify the effectiveness of the MS of 7th and 8th octave bands. Table 4.2 shows Pearson correlation coefficients between the results of subjective evaluation and the calculation results of each parameter. As shown in Table 4.2, the Pearson correlation coefficient between the subjective assessments of fluctuation and the MS of the 7th octave band was extremely high (0.961, $p < 0.01$). This significant correlation (see also Fig. 4.2) suggests, first, that the MS of the 7th octave band can almost completely describe the subjective perceived fluctuation of VIWN and, second, that the MS is applicable for real-recorded VIWN. Therefore, it can be concluded that the MS of the 7th octave band is valid for the assessment of the fluctuation VIWN; we can predict the subjective evaluation of VIWN fluctuation by calculating the MS of 7th octave band. Moreover, the Pearson correlation coefficient of the MS of the 8th octave band was also significant, (0.923, $p < 0.01$) (see Table 4.2).

However, contrary to the results of the previous test in Section 3.3.1, loudness was strongly correlated with the subjectively perceived fluctuation of VIWN. This result is consistent with the findings reported in previous studies [5,6] suggesting that loudness is a crucial factor for VIWN quality. It shows that louder wind noise can be perceived as more fluctuating inside the vehicle. The Pearson correlation coefficient between fluctuation strength and the results of subjective evaluation was 0.760 ($p < 0.01$), while that of loudness was relatively high (0.903, $p < 0.01$). Fluctuation strength in the 7th and 8th octave band showed much lower Pearson correlation coefficients: -0.424 ($p = 0.07$) and -0.628 ($p < 0.01$), respectively. Therefore, we can conclude that the MS of the 7th octave band is most highly correlated with the subjectively perceived fluctuations of VIWN, while both loudness and the MS of 8th octave band are also related to the subjective evaluation.

5. Discussion: Hierarchical linear regression analysis

Based on the results of the correlation analysis outlined in Section of 4.3, it was concluded that the MS can describe and predict the subjective evaluation of the fluctuation of VIWN. However, three objective parameters i(loudness and the MS of 7th and 8th octave bands) were all identified to be highly correlated with subjective evaluation to the fluctuation of the VIWN. To compare the effectiveness of these three parameters and to develop a relevant psychoacoustic model of this phenomenon, hierarchical linear regression was performed.

Linear regression analysis [20], which is based on the ordinary least square (OLS) method, is commonly used to define the relationship between dependent and independent variables. The OLS method is the minimization of the loss function which is defined as follows (see Eq. (8)):

$$L = lo(a,b) = \sum_{i=1}^{n}\left(y_i - \hat{y}_i\right)^2, \tag{8}$$

where y_i is a dependent variable, and $\hat{y}_i$ is a regression equation. In other words, OLS indicates the minimization of the square sum of deviation between the observed and estimated values. If there is only one dependent variable, the relation equation can be defined as follows (see Eq. (9)):

$$\hat{y} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \cdots, \tag{9}$$

where $x_1, x_2, \cdots$ are independent variables, and $\beta_0, \beta_1, \cdots$ are regression coefficients which can be determined using the correlation coefficients between dependent and independent variables. Linear regression analysis can be applied to establish the prediction model of subjective responses using objective measures of the stimuli [18].

With regard to variable selection, stepwise or hierarchical method can be employed to optimize the regression equation from a large set of variable. In particular, hierarchical variable selection method, i.e. hierarchical linear regression, can select variables and enter them into the regression model based on their importance of underlying theory [21,22]. Moreover, we can also consecutively add independent variables for each regression model, so that to evaluate the differences in R^2 of each model for construction of the optimal regression model; we can determine whether a specific independent variable can improve the prediction of a dependent variable via hierarchical linear regression.

As the lowest threshold level in quiet occurs around 2-5 kHz [12], the human auditory perception of sound pressure level is very sensitive near 2-5 kHz. Moreover, the Pearson correlation coefficient of the MS of the 7th octave band (2800-5600 Hz) was the highest (0.961, see Table 4.2). Therefore, we selected the MS of the 7th octave band as the independent variable in Step I (see Table 5.1). Subsequently, we added the MS of 8th octave band (for which the Pearson correlation coefficient was 0.923), the second highest, in Step II. Finally, in Step III, loudness was added to the regression model. For these three regression models, the result of subjective evaluation of 19 stimuli was selected asthe dependent variable. Table 5.1 shows the results of hierarchical linear regression analysis. Step I (R^2 = 0.961, $F(1,17) = 206.309$, $p < 0.01$) and Step II (R^2 = 0.965, $F(2,16) = 108.606$, $p < 0.01$)) showed small differences in $R^2$and F ($\Delta R^2 = 0.008$, $\Delta F(1,16) = 1.754$, $p = 0.204$). Steps II and III ($R^2 = 0.966$, $F(3,15) = 68.903$, $p < 0.01$)) also showed small differences in R^2 and F ($\Delta R^2 = 0.001$, $\Delta F(1,15) = 0.211$ ($p = 0.653$)). Therefore, we can conclude that the MS of 8th octave band and loudness may not improve the prediction of the subjectively perceived fluctuation of VIWN beyond the one provided by the MS of the 7th octave band. Moreover, 96 percent of the variance in subjectively perceived fluctuation of the VIWN was accounted for by only the MS of the 7th octave band, suggesting that this regression model is optimal; the subjective assessment of the fluctuation of the VIWN can described by the MS of the 7th octave band. Consequently, we can define the psychoacoustic model for the fluctuation of the VIWN as the MS of the 7th octave band. The 7th octave band corresponds to the frequency range from 2800 Hz to 5600 Hz. Accordingly, we need to concentrate on this frequency range in order to reduce the perceived fluctuation of the VIWN. Moreover, MS of the 7th octave band can be applied to indicate perceived fluctuation in other broadband noises, as wind noise belongs to broadband noises. However, optimal regression model obtained from hierarchical regression analysis would not indicate that MS is independent from loudness. Further research is needed to determine the relationship between MS and loudness.

Table 3.1. Results of calculation of psychoacoustic metrics of 25 stimuli. The unit of loudness is sone, and 1 sone is the amplitude of 40 dB and 1 kHz tone. The unit of fluctuation strength is vacil and, for a 60 dB, 1 kHz tone 100% amplitude-modulated at 4 Hz produces 1 vacil. Since all stimuli employed identical carrier noise, loudness values are less variable than those of fluctuation strength.

Sample number	Fluctuation strength (vacil)	Loudness (sone)
1	0.0437	6.23
2	0.0442	6.25
3	0.0431	6.22
4	0.0436	6.24
5	0.0438	6.23
6	0.0451	6.35
7	0.0425	6.26
8	0.0431	6.25
9	0.0441	6.25
10	0.044	6.24
11	0.0484	6.31
12	0.046	6.24
13	0.0466	6.26
14	0.0442	6.25
15	0.0445	6.24
16	0.0388	6.22
17	0.0492	6.22
18	0.0482	6.25
19	0.0502	6.28
20	0.0496	6.26
21	0.0659	6.43
22	0.0526	6.32
23	0.0529	6.24
24	0.0531	6.25
25	0.0478	6.25

Table 3.2. Results of correlation analysis between the subjective evaluation and psychoacoustic metrics (fluctuation strength and loudness). The *p*-values of the Pearson correlation coefficients are below 0.05.

		Fluctuation strength	Loudness
Subjective evaluation	Pearson correlation coefficient	0.575	0.460
	p-value	0.003	0.021
	N	25	25

Table 3.3. Results of calculation of modulation strength (MS) for each octave band (from f_c=500 Hz to f_c=8000 Hz)

Sample number	Modulation strength for each octave band (dB SPL)				
	4th (f_c=500 Hz)	5th (f_c=1000 Hz)	6th (f_c=2000 Hz)	7th (f_c=4000 Hz)	8th (f_c=8000 Hz)
1	34.6710	26.2594	20.5480	9.1330	4.9946
2	34.2483	25.5873	19.7592	8.3512	4.9231
3	34.1555	25.4083	19.4056	8.2621	4.1564
4	34.2433	25.8253	19.0808	8.4560	4.2934
5	34.1917	25.7521	19.3446	7.9839	4.5535
6	34.4825	27.5437	20.7348	11.9798	8.4192
7	34.1788	26.8980	20.3834	10.2003	6.1689
8	34.1221	26.9210	19.4371	10.0566	5.7850
9	34.3758	26.8031	19.3799	9.5180	5.8048
10	34.5060	26.8626	19.4025	9.3271	5.3585
11	35.9887	29.1443	22.9088	12.8306	9.0852
12	34.3090	27.6529	20.7841	11.4629	7.3901
13	34.8279	27.2667	19.7442	10.1715	6.7788
14	34.2049	25.6751	20.5838	10.5607	6.8613
15	34.1790	25.5859	20.5170	10.5388	6.4843
16	36.4455	30.6996	22.9600	15.0035	10.9547
17	35.7233	28.8710	21.0191	12.7059	8.9779
18	35.0752	27.9969	20.6748	12.0319	8.1930
19	35.3653	27.4288	20.4396	10.5952	7.4096
20	35.3311	27.3563	20.3341	10.5324	7.1549
21	37.7663	28.4255	24.4826	15.7753	12.0756
22	35.1962	28.1733	22.5325	13.3082	9.7622
23	35.7147	26.3683	22.2201	12.1284	8.5595
24	35.5749	27.6490	21.2473	11.4570	8.4066
25	34.6289	26.5681	21.9676	12.3917	8.2484

Table 3.4. The Pearson correlation coefficients between subjective evaluation and MS of each octave band ($p < 0.01$ for all cases, N = 25, DF = 23)

		Modulation strength for each octave band				
		4th f_c=500 Hz	5th f_c=1000 Hz	6th f_c=2000 Hz	7th f_c=4000 Hz	8th f_c=8000 Hz
Subjective evaluation	Pearson correlation coefficient	0.751	0.777	0.832	0.929	0.952
	P-value	0.000	0.000	0.000	0.000	0.000
	N	25	25	25	25	25

Table 4.1. Results of calculation of psychoacoustic metrics of 19 stimuli (vehicle types, velocity, and yaw angle conditions were considered)

Sample number	Fluctuation strength (vacil)	Loudness (sone)
1	0.0513	6.81
2	0.0637	9.00
3	0.0492	4.54
4	0.0598	8.07
5	0.0687	9.72
6	0.0612	7.29
7	0.0617	11.90
8	0.0712	16.70
9	0.0581	7.89
10	0.0702	14.60
11	0.0593	9.80
12	0.0661	12.90
13	0.0696	16.40
14	0.0539	8.15
15	0.0567	10.40
16	0.0604	12.80
17	0.0617	13.70
18	0.0675	18.00
19	0.0682	25.10

Table 4.2. The Pearson correlation coefficients between subjective evaluation and the calculation results of four parameters (fluctuation strength, loudness, MS of the 7th and 8th octave bands) for 19 stimuli ($p < 0.01$ for all cases, N = 25, DF = 23)

		Fluctuation strength	Loudness	MS of the 7th octave band (f_c=4000 Hz)	MS of the 8th octave band (f_c=8000 Hz)
Subjective evaluation	Pearson correlation coefficient	0.760	0.903	0.961	0.923
	P-value	0.000	0.000	0.000	0.000
	N	19	19	19	19

Table 5.1. The results of hierarchical linear regression. Changes in R square and F statistic suggest that Step I is the optimal regression model. Since p-values of Steps II and III are above 0.05, the optimal regression equation can be obtained by the MS of the 7th octave band.

	R^2	Standard error	Changes in statistics				
			ΔR^2	ΔF	DF 1	DF 2	p-value
Step I	0.924	2.6323	0.924	206.309	1	17	0.000
Step II	0.931	2.5759	0.008	1.754	1	16	0.204
Step III	0.932	2.6418	0.001	0.211	1	15	0.653

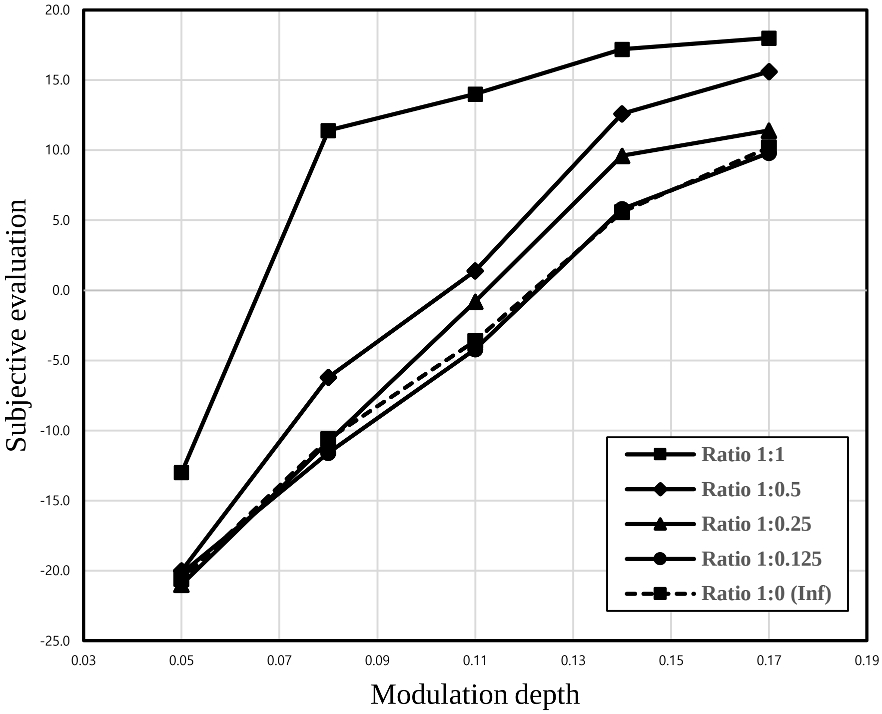


Fig. 3.1. The results of the jury test. The abscissa is the modulation depth of 4 Hz (m_t), and the ordinate is subjectively perceived fluctuation scores. The larger score means more fluctuating noise. Five lines represent five cases of depth ratio between the modulation depth of 4 Hz (m_t) and that of the other frequencies (m_i). For each case of depth ratio, a larger modulation depth of 4 Hz (m_t) leads to more fluctuating noise.

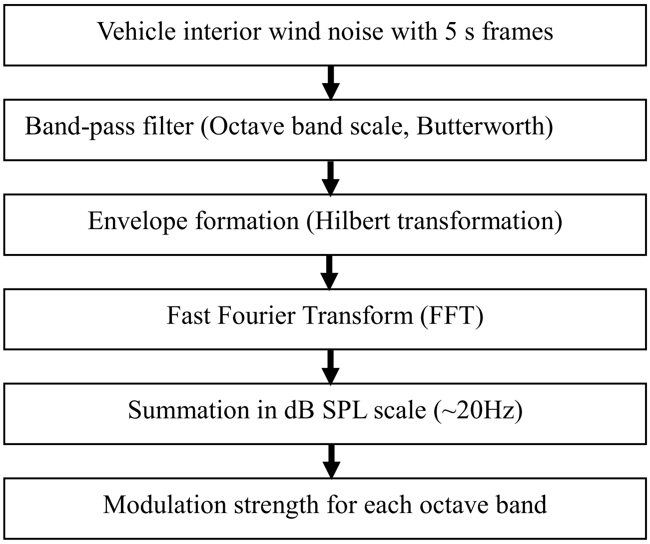
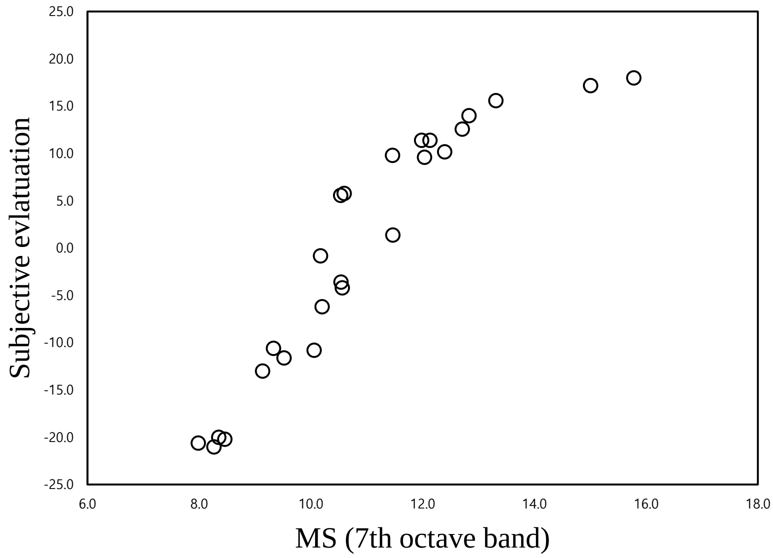
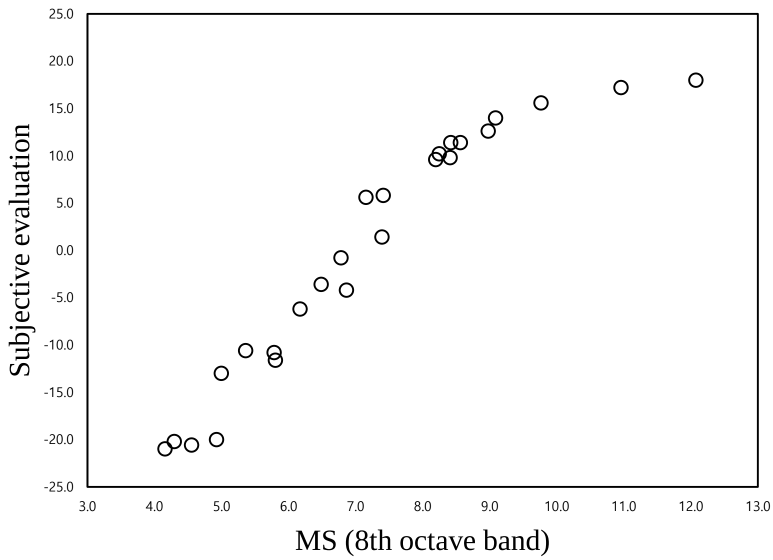


Fig. 3.2. A schematic flow diagram illustrating the calculation procedure of the MS. The duration of each VIWN stimulus for the jury test was 5 s, and the stimulus was given as an input for this calculation. Band-pass filter in octave band scale was employed to concentrate on the frequency range of interest. After the envelope formation, modulation factors (dB scale) for each modulation frequency were summed, and the resultant value was defined as MS.

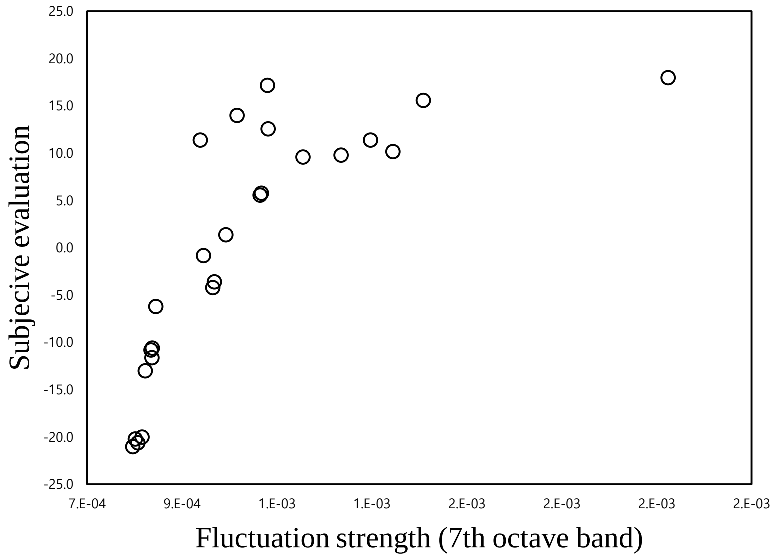


(a)

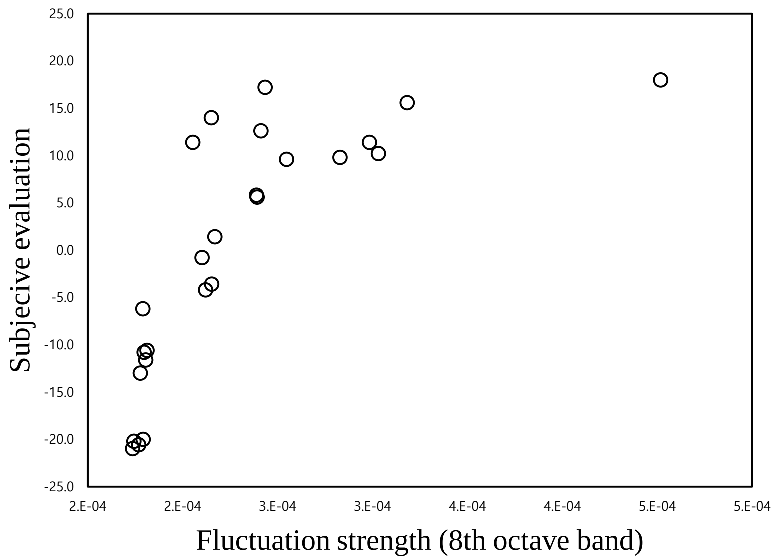


(b)

Fig. 3.3. Scatter plots between the subjectively perceived fluctuation and (a) MS of the 7th octave band (2800 – 5600 Hz), (b) MS of the 8th octave band (5600 – 11200 Hz). The Pearson correlation coefficients are 0.929 and 0.952, respectively ($p < 0.01$, DF = 23). The scatter plots and Pearson correlation coefficients show a strong correlation between the subjective evaluation and MS of the 7th and 8th octave bands.



(a)



(b)

Fig. 3.4. Scatter plots between the subjectively perceived fluctuation and fluctuation strength of (a) the 7th octave band (2800 – 5600 Hz), (b) the 8th octave band (5600 – 11200 Hz). The Pearson correlation coefficients are 0.757 and 0.741, respectively ($p < 0.01$, DF = 23), and these values indicate that a much lower correlation between subjective evaluation and fluctuation strength of the 7th and 8th octave bands than MS.

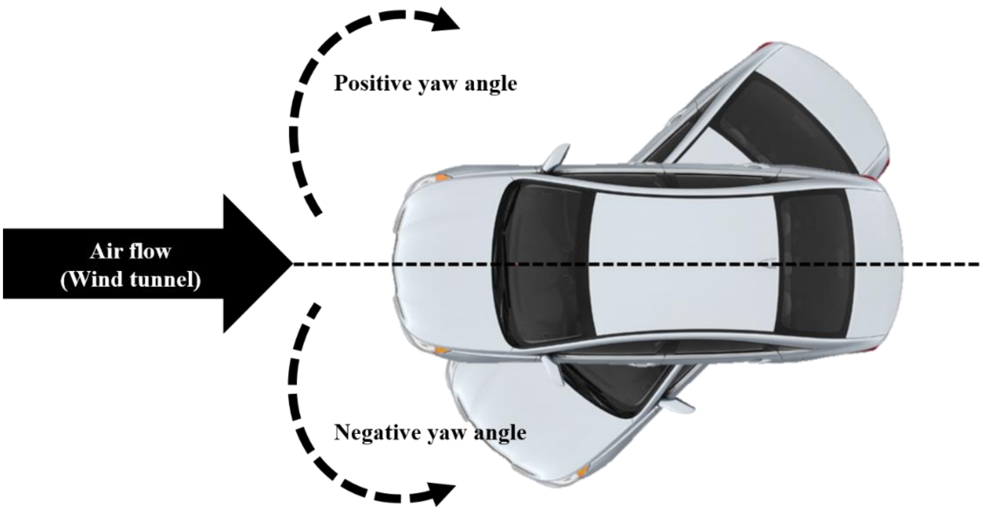


Fig. 4.1. Yaw angle conditions. Four conditions were considered: parallel (zero yaw angle), 8 degrees in the negative direction, 8 degrees, and 10 degrees in the positive direction.

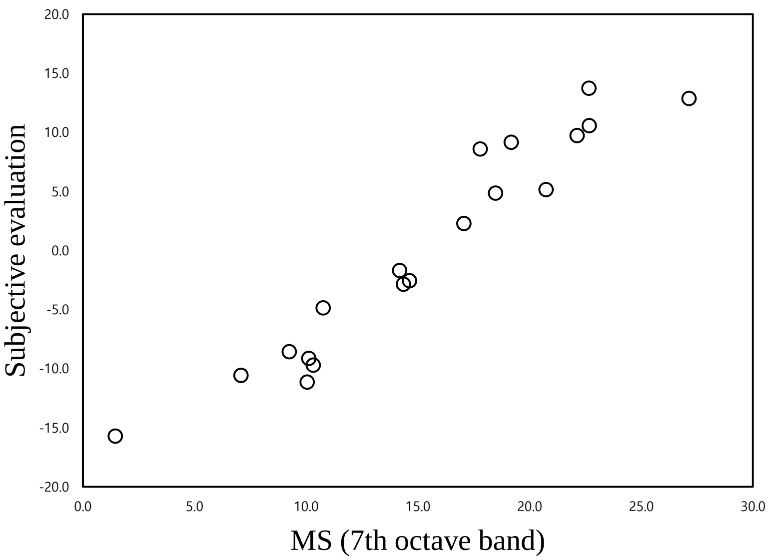


Fig. 4.2. Scatter plot between the results of subjective assessment for 19 stimuli and MS of the 7th octave band (2800 – 5600 Hz). The Pearson correlation coefficient is 0.961 ($p < 0.01$, DF = 17), and shows that subjectively perceived fluctuation of 19 stimuli recorded inside the vehicle is highly related to the MS of the 7th octave band.

6. Conclusions

The present study sough to investigate the perception of the VIWN fluctuation and to develop an indicator of the subjective perception of the VIWN fluctuation. Since wind noise inside the vehicle is a broadband noise, only amplitude modulation was considered. In the first experiment, fluctuating VIWN was determined as a SAM noise, and 25 stimuli were made using the partially weighted pink noise with various modulation components. Although fluctuation strength is widely used to describe subjective perception of fluctuating noise, the Pearson correlation coefficient between fluctuation strength and the subjective assessment of 25 stimuli was not significant (R = 0.575, p < 0.01). However, the MS proposed in this paper was strongly correlated with the subjectively perceived fluctuation of the VIWN. To examine the validity of the MS, 19 stimuli recorded inside the vehicle were used in the second experiment. The results of subsequent correlation analysis showed that three parameters (loudness and the MS of 7th and 8th octave bands) were related to the subjective evaluation results. Thereafter, hierarchical linear regression analysis was conducted to verify which parameter was dominant, and it was concluded that the MS of the 7th octave band can fully explain the subjectively perceived fluctuation of VIWN. In sum, the MS of the 7th octave band was determined as the psychoacoustic model for fluctuation of the VIWN in the present study.

Since the 7th octave band corresponds to the frequency range between 2800 to 5600 Hz, it is necessary to focus on this frequency range when reducing the fluctuation of VIWN. Moreover, the psychoacoustic model proposed in the present paper can be applied to describe fluctuations of other broadband noises, as wind noise is a common example of broadband noises. However, the dependency of the MS on loudness should be investigated further to develop an improved prediction model, which would be free from loudness, for fluctuating wind noise.

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초 록

고속 주행 조건에서 사용자의 만족도는 외부 유동에 의해 발생하는 차량 실내 윈드노이즈에 기인한다. 이러한 차량 실내 윈드노이즈가 흔들리는 경우, 불쾌감이 증폭될 수 있으며 안전성에 대한 불안감 또한 야기될 수 있으므로 차량 실내 윈드노이즈의 변동감에 대한 정량적 연구가 필요하다. 따라서 본 연구는 차량 실내 윈드노이즈의 변동감을 평가 및 예측하기 위한 음향심리학적 모델 개발을 목표로 한다. 1차 실험에서 윈드노이즈를 정현파 형상으로 변동하는 광대역 소음으로 정의하고 25개의 샘플을 제작하여 청음 평가를 진행하였다. 그 결과로, 새로운 변동감 인자를 제안했으며, 2차 실험에서는 변동감 인자에 대한 유효성 검증을 위해 실제 차량 내부에서 녹음한 음원을 사용하여 청음 평가를 진행하였다. 상관 분석 결과, 라우드니스와 7, 8차 옥타브 밴드의 변동감 인자가 청음 평가 결과와 유의미한 상관 관계에 있음을 확인했으며, 위계적 회귀 분석을 통해 7차 옥타브 밴드 변동감 인자가 지배적임을 증명하였다. 이를 통해, 7차 옥타브 밴드의 변동감 인자로 차량 실내 윈드노이즈의 변동에 대한 주관적인 평가를 설명할 수 있다는 결론을 도출하였다.

주요어 : 음질, 윈드노이즈, 변동감, 정현파 진폭 변동, 차량 실내음
학번 : 2016-20669