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Analysis of the HVAC system's sound quality using the design of experiments †

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Abstract

Human hearing is very sensitive to sound, so a subjective index of sound quality is required. Each situation of sound evaluation is composed of Sound Quality (SQ) metrics. When substituting the level of one frequency band, we could not see the tendency of substitution at the whole frequency band during SQ evaluation. In this study, the Design of Experiments (DOE) is used to analyze noise from an automotive Heating, Ventilating, and Air Conditioning (HVAC) system. The frequency domain is divided into 12 equal parts, and each level of the domain is given an increase or decrease due to the change in frequency band based on the "loud" and "sharp" sound of the SQ analyzed. By using DOE, the number of tests is effectively reduced by the number of experiments, and the main result is a solution at each band. SQ in terms of the "loud" and "sharp" sound at each band, the change in band (increase or decrease in sound pressure) or no change in band will have the most effect on the identifiable characteristics of SQ. This will enable us to select the objective frequency band. Through the results obtained, the physical level changes in arbitrary frequency domain sensitivity can be determined.

***Keywords*:** Vehicle noise; Sound quality; HVAC; Loudness; Sharpness; DOE

1. Introduction

Recently, quieter driving conditions have become available due to developments in car noise reduction techniques. Until recently, vehicle design has been focused only on performance, while consumers' demand for a comfortable riding environment has increased. Therefore, vehicles are caught between their original design goal and cultural demands. People ride vehicles everyday, and drivers listen to music or make phone calls using their cellphone. Many people thus change vehicles' audio system, and it can be said that the interest regarding interior noise and acoustics has increased. Furthermore, the noise problem has become an important element that must be considered in vehicle design in order for decibel vehicle noise not to influence vehicle sales. [1] The noise reduction in vehicle design includes the driver's cognition level to noise elements, such as the vehicle HVAC system noise that becomes masked under noisy driving conditions. This noise level is not high by a whole noise level, but it influences subjective cognition that in turn causes the driver's emotional response to be pronounced or unpleasant.

Sound can be sensitive and subjective for a person. In particular, the noise people hear intensely is difficult to express in terms of an objective numerical value, and so a subjective standard which is applicable to a person's sensitivity is required. [2, 3] Many researchers are changing the SQ characteristics of vehicle noise through changing the frequency characteristics of the noise spectrum and performing hearing

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tests consisting of changing the characteristics of vehicle vibration and fluid noise, among others. A weakness of the results from the hearing tests of modified noise regarding a specific objective frequency band level is that it does not take into account the tendency of the whole frequency band. In addition, the analysis is not sensitive enough to detect changes in SQ metrics through changing only the systems, making it difficult to directly control objective SQ metrics.

In this study, the whole frequency band is divided into 12 HVAC system noises and then edited by modifying (increasing or decreasing) the noise level. Hearing tests are performed, and the tendency regarding loud and sharp noises is analyzed by subjective SQ metrics. Through main effect analysis of the frequency band and value estimation, we aim to choose an objective frequency of SQ that is highly sensitive in terms of the relevant metrics of the systems. [5]

2. Experiment

2.1 Composition of the experiment

Although noise data are necessary to perform hearing tests, the collected HVAC noise data can predict only the simple characteristics of SQ. Therefore, they are divided into 12 frequency bands by processing whether an increase or decrease at each band level was made by the various sources and by performing hearing tests on them. This requires a considerable amount of noise data and experiment cases. To improve this, noise sources were changed, reducing the experimental number of cases effectively using DOE, and hearing tests were performed on 30 people. DOE refers to the plan or method of conducting an experiment. It refers to the experimentation of the problem to be solved and how to obtain as much data as possible from the least number of experiment times. [7]

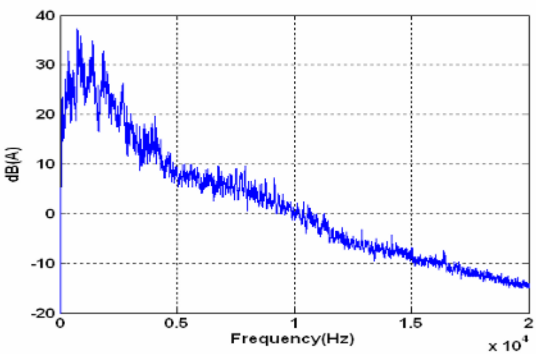

Fig. 1. The frequency characteristics of the original sound at the driver's seat according to step 4.

2.1.1 Object noise

HVAC noise as used in the experiment refers to the noise produced by the HVAC system in a 3000cc full-size vehicle manufactured by a Korean company. In the current research, the frequently used step 4 noise of the cool mode and the high level of 45.9dB (A) was chosen. Fig. 1 shows the frequency characteristics of the original sound to 20kHz.

2.1.2 Factor composition of DOE

DOE was used to modify the noise to be used in the hearing tests. The 12 factors are shown in Table 1. These factors are the 24 Bark bands recognized as a person's hearing range, which were reorganized into 12 bands. In other words, two bark bands were replaced by one wide band.

2.1.3 Level composition of DOE

The level used in the noise modification was set to be the minimum level 3dB, which can divide sound change to edge. Many researchers similarly use this method of noise reduction. In this study, to analyze the various characteristics of SQ by increasing the

Table 1. The 12 divisions by Bark and frequency.

Factor	Bark	frequency	
		lower	upper
A	1, 2	0	200
B	3, 4	200	400
C	5, 6	400	630
D	7, 8	630	920
E	9, 10	920	1270
F	11, 12	1270	1720
G	13, 14	1720	2320
H	15, 16	2320	3150
J	17, 18	3150	4400
K	19, 20	4400	6400
L	21, 22	6400	9500
M	23, 24	9500	15500

Table 2. Control factors and their levels .

Level No.	1	2	3
dB	+3dB	0dB	-3dB

Table 3. Orthogonal array and factor assignment.

Experiment No.	Factor											
	A	B	C	D	E	F	G	H	J	K	L	M
1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2
11	2	1	2	3	2	3	1	2	3	1	2	3
12	2	1	2	3	3	1	2	3	1	2	3	1
13	2	2	3	1	1	2	3	2	3	1	3	1
14	2	2	3	1	2	3	1	3	1	2	1	2
15	2	2	3	1	3	1	2	1	2	3	2	3
16	2	3	1	2	1	2	3	3	1	2	2	3
17	2	3	1	2	2	3	1	1	2	3	3	1
18	2	3	1	2	3	1	2	2	3	1	1	2
19	3	1	3	2	1	3	2	1	3	2	1	3
20	3	1	3	2	2	1	3	2	1	3	2	1
21	3	1	3	2	3	2	1	3	2	1	3	2
22	3	2	1	3	1	3	2	2	1	3	3	2
23	3	2	1	3	2	1	3	3	2	1	1	3
24	3	2	1	3	3	2	1	1	3	2	2	1
25	3	3	2	1	1	3	2	3	2	1	2	1
26	3	3	2	1	2	1	3	1	3	2	3	2
27	3	3	2	1	3	2	1	2	1	3	1	3

noise that is not only reduced, three levels were se lected: +3, 0, and -3 dB (Table 2).

2.1.4 The noise modification and orthogonal array

If the experiment is constructed using twelve factors and three levels with the perfect arrangement method, more than fifty thousand data points would be required. This is ineffective in terms of cost and time, and thus the orthogonal array was applied in the experiment (Table 3). We assumed that interactions could not appear among the factors. [7]

3. Subjective evaluation

According to the change in each factor level (sound and pressure level change in the frequency band) pertaining to the testing results of the "loud" and "sharp" noise, main effect analysis is performed to recognize how the characteristics of SQ metrics change. The mean values of the subjective hearing tests are shown in Table 4.

Table 4. Mean descriptive statistics of "Loud" and "Sharp".

Experiment No.	Loud	Sharp	Experiment No.	Loud	Sharp
1	3.9	4.5	15	3.5	3.9
2	3.6	4.6	16	3.0	3.9
3	4.4	3.4	17	5.3	4.5
4	4.0	3.7	18	4.9	4.3
5	5.0	4.4	19	3.3	5.0
6	4.5	3.5	20	4.7	5.0
7	4.8	3.7	21	4.8	4.5
8	3.9	3.1	22	4.2	4.6
9	5.2	4.7	23	4.0	4.3
10	4.7	3.8	24	4.0	4.1
11	6.0	4.0	25	4.9	4.9
12	3.6	4.4	26	5.1	4.5
13	3.8	4.1	27	3.6	5.2
14	4.7	4.2			

3.1 Subjective hearing tests

After explanation of the procedure, 30 men who had normal hearing sense, who were in their 20s~40s, and who used the Noise-Book made by the Head Acoustics performed the tests. The Semantic Differential Method (SDM) measured the subjective responses using a seven-point scale. [8]

When either of the two testing factors "loud" or "sharp" is evaluated as "high," a full mark of seven points is given, and in the opposite case, one point is given. The noise sources with a duration of 10s were presented randomly. This study not only measures people's subjective response to "loud" and "sharp" HVAC noise but also objectively analyzes sensitivity by changing the level of each frequency band. The standard point is established as four by using the original noise for more accurate testing results.

3.2 The main effect analysis of "Loud"

The main effect of the subjective "loud" is shown in Fig. 2, with a lower mean value indicating a better result. The subjective loud point decreased when reducing the sound pressure level of the A (0~200Hz), L (6400 ~ 9500Hz), and B (200~400Hz) bands. The order of bands beginning with the largest main effect is A (0 ~ 200Hz), B (400 ~ 630Hz), and L (6400 ~ 9500Hz). By reducing the SPL of the low frequency band, the subjective loud point can be decreased.

3.3 The main effect analysis of "Sharp"

The main effect of the subjective "sharp" is shown by the sound pressure level depicted in Fig. 3; the lower the mean value, the better the result. The mean value can be decreased when the level number is one (sound pressure level increase) at the A band of the low frequency, and three (sound pressure level reduction) around 1000Hz and greater than 6000Hz of the high frequency band. The noise level is sensitive to a person around 1000Hz. The results indicated that the main effect is high with the A (0 ~ 200Hz), L (6400 ~ 9500Hz), and M (9500 ~ 15500Hz) bands. This relates to a more effective result when controlling the A, L, and M bands than when controlling the other bands. Specifically, to reduce the "sharp" of HVAC noise, it is most effective to increase the sound pressure level of the A band.

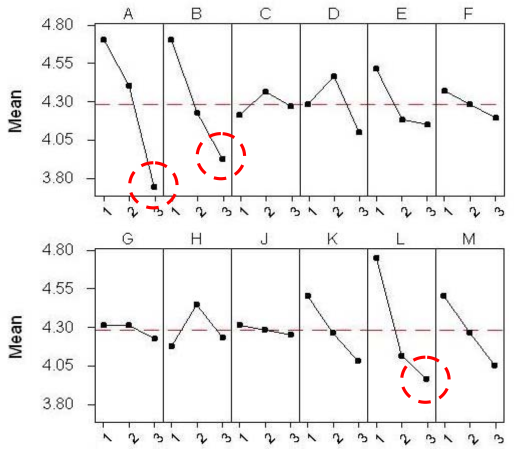

Fig. 2. The main effect for the mean of "Loud".

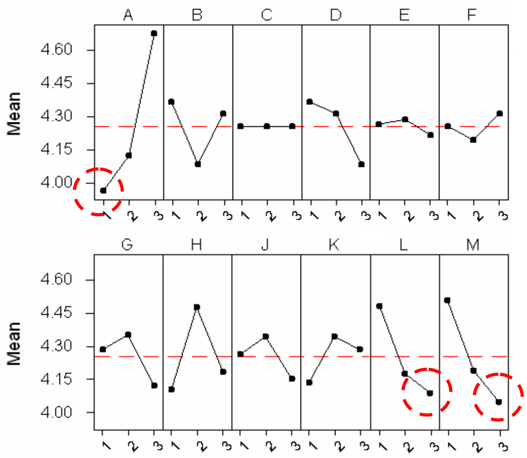

Fig. 3. The main effect for the mean of "Sharp".

3.4 The result of SQ characteristic analysis

In the case of the "loud" result, the HVAC noise is distributed significantly around the low frequency band and shows "loud" to be decreasing when the sound pressure level around the low frequency band is reduced. The main effect of the A band (0 ~ 200Hz) is high, indicating that using a method of decreasing the sound pressure level can reduce the subjective "loud." In the case of "sharp," the result is analyzed by masking the high frequency with the low frequency; this is done through reducing the high frequency band and increasing the low frequency band of the sound pressure level relatively. The objective frequency bands of SQ that originate in each SQ characteristic are as follows: in the case of "loud," 0 ~ 400Hz, 6400 ~ 9500Hz, and in the case of "sharp," 0 ~ 200Hz, 6400 ~ 15500Hz. The objective frequency band of the SQ of the "loud" and "sharp" result is similar but requires a selection level for the correct situation because of the contradictory results regarding the level change.

4. Verification of the experiments

Table 5 demonstrates the optimum level of combining the frequency bands through main effect analysis. The noise is modified by matching it to each frequency band and level in order to verify the accuracy of the experiment. Finally, hearing tests are executed in an identical manner. The participants for the verification are the same people as in the main ex periment. The optimum value using the orthogonal

Table 5. Predicted optimal level of "Loud" and "Sharp".

Sound Quality	A	B	C	D	E	F	G	H	J	K	L	M
Loud	3	3	1	3	3	3	3	1	3	3	3	3
Sharp	1	2	2	3	3	2	3	1	3	1	3	3

array is 3.0 points of experiment No.16 in the case of "loud," and the result of the hearing test executed for verification is 2.8 points. Similarly, the optimum value of "sharp" is 3.1 points of experiment no.8, and the verification result is 3.0 points. Consequently, as shown in the above, the modified noise can be judged as correct.

5. Conclusions

In this study, the characteristics of SQ pertaining to "loud" and "sharp" for HVAC noise are analyzed by using DOE; this is done by changing the sound pressure level of the frequency band. This is different from the analysis of SQ characteristics by increasing or reducing the sound pressure level near the limited frequency band. Since it can encompass tendencies pertaining to whole frequency bands, the objective frequency bands can be chosen according to each SQ characteristic. In addition, the SQ characteristics can change not only by reducing but also by increasing the sound pressure level. Specifically, SQ metrics such as "sharp" that happen in the high frequency band is judged to be useful by the method of reducing "sharp" through increasing the low frequency. However, this study has the following limitations. The loudness and sharpness contribute to the overall expression of SQ. However, in this study, we assumed that interactions could not appear among the factors so we demonstrated the SQ parameters separately.

Existing research on SQ has only gone as far as knowing the SQ characteristics which are changed by altering or controlling the analysis system. In this study, by choosing and changing the objective frequency of SQ, analyzing it, and then choosing a system to control, a more direct research that executes SQ control has been demonstrated. A method that can change the sound pressure level of the frequency band and analyze the SQ characteristics using DOE can give results regarding each frequency band and can estimate the value even if the sound pressure level of the frequency band about the noise of equal or similar system is changed. Since SQ characteristics can be expected without executing repeated hearing tests on the results by shape alteration or later shifting the frequency of interest, it could become a new alternative method in reducing the number of times a hearing test is given.

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