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ANALYSIS OF THE HVAC SYSTEM'S "LOUD" AND "SHARP" USING DESIGN OF EXPERIMENTS

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Abstract

Since human hearing is very sensitive to sound, a subjective index of sound quality is required. Each situation of sound evaluation is composed of the 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 the SQ evaluation. In this study, a 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 twelve equal parts and each level of the domain is given an increase or decrease due to the change of frequency band based on the 'loud' and 'sharp' 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 'loud' and 'sharp' at each band, the change of band (increase or decrease of sound pressure) or no change of 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 of the arbitrary frequency domain sensitivity can be adapted..

1. INTRODUCTION

Recently, quieter driving conditions became available due to developments in car noise reduction techniques. Until recently, the vehicle design was that of a machine that depends only on performance but consumers' request for a comfortable and agreeable environment increased. The vehicle is caught between its original design intent and cultural demands. People get into vehicles everyday and drivers listen to music or make phone calls using a cell phone. Many people change the vehicle's audio system and the interest regarding interior noise and acoustics is increasing daily. Furthermore, the noise problem has become an important element and must be considered in the vehicle design in order for the decibel vehicle noise not to influence its sale.[1] The noise reduction in vehicle design included 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 whole noise level but it influences the subjective cognition causing the driver's emotional response to be pronounced or unpleasant.

Sound can be sensitive and subjective for a person. In particular, the noise people feel intensely is difficult to express by an objective numerical value, and a subjective standard, which is applicable to a person's sensitivity, is required.[2,3] Many researchers are changing SQ characteristics of the vehicle noise through changing the frequency characteristics of the noise spectrum and performing hearing tests consisting of changing the characteristics of vehicle vibration and fluid noise etc. A weakness of the results from the hearing tests of the 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 of 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 twelve 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 the main effect analysis of the frequency band and value estimation, we wish to choose an objective frequency of SQ is highly sensitive in terms of the relevant metrics of the systems.[5]

2. EXPERIMENT AND EVALUATION

2.1 Composition of experiment

Although noise data is necessary to perform hearing tests, the collected HVAC noise data can predict only simple characteristics of SQ. Therefore it is divided into twelve frequency bands by processing whether an increase or decrease at each band level was made by the various sources and performing hearing tests with 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 with thirty people.

2.1.1 The Object noise

The HVAC noise used in an experiment is noise produced by a HVAC system in a 3000cc full-size vehicle manufactured by a Korean company. During the current research, the frequently used step 4 noise of cool mode and the high level of 63dB(A) was chosen.

2.1.2 Factor composition of DOE

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

Table 1 The twelve 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

2.1.3 Level composition of DOE

The level used in the noise modification was chosen to be a minimum level 3dB that can divide sound change to edge actually. Many researchers similarly use this method of noise reduction. In this study, to analyze various characteristics of SQ by increasing the noise that is not only reduced, three levels were selected of +3, 0 and -3 dB (table 2).

Table 2 Control factors and their levels

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

2.1.4 The noise modification and orthogonal array

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

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

2.2 Subjective hearing tests

After explanation of the procedure, thirty men who had a normal ability of hearing sense using the Noise-Book made by the Head Acoustics performed the tests. The Semantic Differential Method (SDM) measured subjective responses with a seven point scale.[8] When either of the two testing factors ‘loud’ or ‘sharp’ are evaluated as 'high', a full mark of seven points is given and in the opposite case, one point is given. The order of experiments was randomly performed. This study not only measures people's subjective response to ‘loud’ and ‘sharp’ HVAC noise, but can objectively analyze the sensitivity by changing the level of each frequency band. The standard point is established as four by using the original noise for accurate testing results

3. EXPERIMENT AND EVALUATION

According to the change of each factor level (sound and pressure level change of the frequency band) pertaining to the testing results of the ‘loud’ and ‘sharp’ noise, the main effect analysis is performed to recognize how characteristics of SQ metrics change. The mean values of these results 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 The main effect analysis of ‘Loud’

The main effect of the subjective ‘loud’ is drawn in Figure 1 with the lower mean value indicating a better result. The subjective loud point decreased when reducing the sound pressure level of the A(0~4000Hz) and B(200~400Hz) bands (Table 4). Conversely, the sound pressure level increased when increasing the L(6400 ~ 9500Hz) band but the subjective loud point decreased. The order of bands beginning with the largest main effect is; A(0 ~ 200Hz), L(6 400 ~ 9500Hz) and B(400 ~ 630Hz). Reducing SPL of the low frequency band and increasing SPL of the high frequency band, the subjective loud point can be decreased.

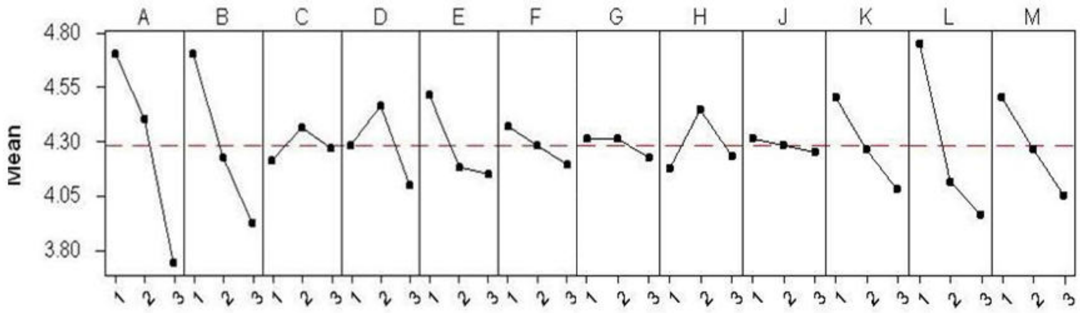

Figure 1 – The main effect for the mean of 'Loud'

3.2 The main effect analysis of 'Sharp'

The main effect of the subjective 'sharp' is drawn by sound pressure level as shown in Figure 2 and 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 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 A, B and C bands than controlling other bands. Specifically, to reduce the 'sharp' of the HVAC noise it is most effective to increase the sound pressure level of the A band.

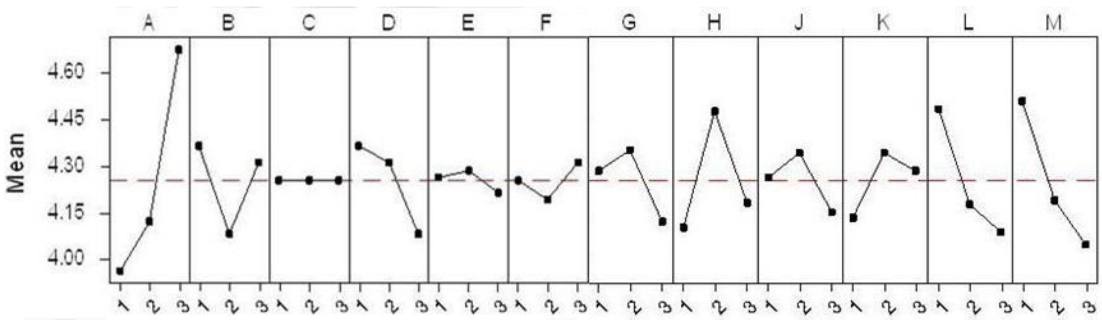

Figure 2 – The main effect for the mean of 'Sharp

3.3 The result of the SQ characteristic analysis

In the case of the 'loud' result, the HVAC noise is distributed significantly around the low frequency band and shows 'loud' decreasing when reducing the sound pressure level around the low frequency band. The main effect of the L band (6400 ~ 9500Hz) is high, indicating a result that can reduce the subjective 'loud' using a method of increasing the sound pressure level. In the case of the 'sharp', the result is analyzed by masking the high frequency with the low frequency by 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 characteristics 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 SQ of the ‘loud’ and ‘sharp’ result is similar but requires a selection level for the correct situation because of the opposing results regarding level change.

4. THE VERIFICATION OF EXPERIMENTS

Table 5 demonstrates the optimum level of combining the frequency bands by the main effect analysis. The noise is modified by being suited to each frequency band and level to verify the accuracy of an experiment. Finally, hearing tests are executed in an identical manner. The optimum value using the orthogonal 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 3.1points of experiment No.8 and the verification result is 3.0 points. Consequently, as shown in the above results, this can be judged as correct.

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

5. CONCLUSION

In this study, the characteristics of SQ pertaining to ‘loud’ and ‘sharp’ for the HVAC noise are analyzed by using DOE by changing the sound pressure level of the frequency band. This is different from analysis of the 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, 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’ by increasing the low frequency.

The existing research of SQ has only gone as far as knowing the SQ characteristics which are changed by altering or controlling the analyzing system. In this study, by choosing and changing the objective frequency of SQ and 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 a repeated hearing test concerning 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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