SUBJECTIVE EVALUATION EXPERIMENT OF AIR-CONDITIONING SOUNDS IN A VEHICLE ACCORDING TO THE DIFFERENCES BETWEEN GENERATIONS

Ryota NAKASAKI[*ab], Takaharu OGATA[a], Hiroshi HASEGAWA[a], Yukio OZEKI[b], Masaharu ONDA[b] and Masao KASUGA[a]

[a] *Graduate school of Engineering, Utsunomiya University, Japan*
[b] *Calsonickansei Corporation, Japan*

ABSTRACT

Recently, sound quality of the air-conditioning sound in a vehicle becomes one of the important elements of the user's preference. To improve quietness in the compartment further, therefore, it is important not only to reduce the sound pressure level (SPL), but also to improve the sound quality. Currently, there are many vehicle segments each of which consists of many vehicle models that have target generations of the users. Therefore, creation of the quality of air-conditioning sounds suited for each target generation is indispensable for vehicle developers. In this paper, we tried to evaluate the air-conditioning sounds from a viewpoint of sound quality according to differences among generations. First, we carried out an experiment to select the suitable words that represent the characteristics of the air-conditioning sounds. As a result, the air-conditioning sounds could be represented by the seven words. Next, we carried out a subjective experiment to investigate differences of feeling of air-conditioning sounds in a vehicle according to various generations using psychoacoustic parameters. As a result, noting that the lower generation subjects evaluated not only the sound characteristics but also thermal feeling of the sound depending on change in the sharpness while the higher generation subjects were hard to evaluate the sharpness of the sounds. Finally, we performed a factor analysis. Then, we extracted two factors and defined as "thermal factor" and "rough factor," respectively. Then, noting that the thermal factor had a strong correlation with the sharpness, and the rough factor had a strong correlation with the loudness.

Keywords: *air-conditioning sound, subjective evaluation, psychoacoustic parameter*

[*] Calsonickansei Corporation, 8 Sakae-cho, Sano-shi, 327-0816, Japan E-mail: ryota_nakasaki@ck-mail.com

1. INTRODUCTION

Recent noise-reduction technologies for mechanical components of a vehicle have made it possible to improve quietness in the compartment of a vehicle drastically [1]. The air-conditioning system in a vehicle, therefore, becomes one of the major noise sources in the compartment. Sounds from the air-conditioning system are generally evaluated in terms of its sound pressure level (SPL), and many countermeasures are done to reduce the SPL. However, it takes much cost to reduce the SPL of the sounds. On the other hand, sound quality of air-conditioning sounds according to user's preference has been gradually paid attention in recent years. It is, therefore, required that sounds from the air-conditioning system are not only reduced but also created as sounds having comfortable feelings.

In this paper, we tried to evaluate sounds originating from the air-conditioning system in a vehicle from a viewpoint of sound quality. First, we investigated words that represent characteristics of the air-conditioning sounds. Next, we carried out a subjective evaluation experiment using the SD (semantic differential) method [2] for the air-conditioning sounds to subjects in various generations. In this experiment, we evaluated not only the SPL but also psychoacoustic parameters of the loudness and sharpness. Finally, we performed a factor analysis to determine major factors that represent characteristics of the air-conditioning sounds.

2. SELECTION OF EVALUATION WORDS

We carried out an experiment to select suitable words that represent characteristics of the air-conditioning sounds in a vehicle.

2.1. Experimental conditions

In a vehicle, users can set the air-conditioning mode freely depending on season, temperature, and purpose. The perceived image of the air-conditioning sounds changes depending on each mode. In this experiment, we used air-conditioning sounds at the following three representative modes; "Vent-mode," that is frequently used in summer, "Foot-mode," that is frequently used in winter, "Defroster-mode," that is used when the window is cloudy. About the air inlet, air was recirculated on Vent-mode, and fresh air was introduced from outside of a vehicle on Foot-mode and Defroster-mode. Figure 1 shows the conditions of the air inlet and outlet on each air-conditioning mode. We set each mode to "Fan-max" means that the fan rotates at the maximum speed, where the air-conditioning sounds are perceived loudest. We used a soundproof room for vehicle, where the ambient background noise was under 40 dB(A) to record the air-conditioning sounds. In the recording, we used two non-directional microphones that were installed at the both ear positions of the driver. We recorded the air-conditioning sounds onto DAT (Digital audio tape) for five kinds of vehicles. In each recording, the engine of the vehicle was idling.

2.2. Experiment

The recorded air-conditioning sounds were presented to the subjects via headphones in a soundproof room (D-30). The SPL of each air-conditioning sound was adjusted to the same level in the vehicle compartment. After each presentation, we asked the subjects to select several words that were appropriate to represent images of the air-conditioning sounds from 120 words list referred to the references [3] and [4].

Seventeen subjects in their 20's, who had normal hearing acuity, participated in the experiment.

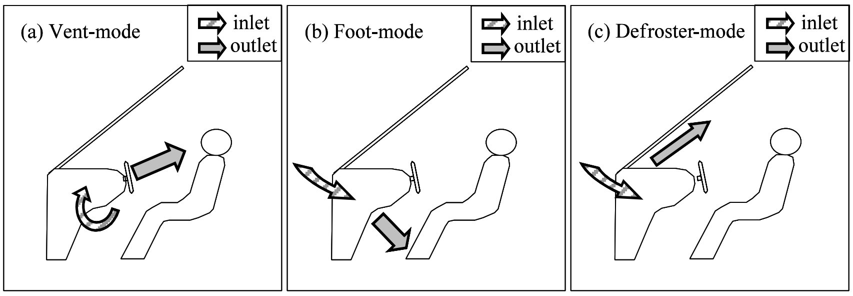

Figure 1: Air conditioning mode (inlet and outlet).

2.3. Results

We performed a cluster analysis to the data obtained from the experiment. Cluster analysis is a method which aims to classify several objects into some groups, i.e. clusters, corresponding to similarities between them. To classify the evaluation words into some groups, we employed a cluster analysis using Pearson's correlation. Pearson's correlation is shown as follows [5]:

$$r = \frac{\sum (x_i - x)(y_i - y)}{(N-1) S_x S_y}, \qquad (1)$$

where r is the correlation coefficient, x_i and y_i are the numbers of selections to respective words for each target sound. x and y are the average values of x_i and y_i, respectively. S_x and S_y are the standard deviations of x_i and y_i, respectively. N is the total number of the target sounds.

Table 1 shows result of the cluster analysis at a case of the correlation coefficient is 0.2. The 120 evaluation words were classified into 10 groups (adjectives) as shown in Table 1. These groups, however, include the adjectives which are not suitable as the evaluation words, since their selection ratios are low. Therefore, we selected adjectives whose selection ratios are more than 15% as the evaluation words. As a result, seven words of "quiet," "refreshing," "heavy," "wide," "muddy," "violent," and "dry" were selected as the evaluation words that represent characteristics of the air-conditioning sounds.

Table 1: Evaluation words selected by a cluster analysis.

Adjective	Standard deviation	Select ratio (%)	Adjective	Standard deviation	Select ratio (%)
quiet	**4.34**	**22.7**	melt	1.23	9.8
cheap	1.06	8.6	**muddy**	**1.99**	**21.2**
refreshing	**1.60**	**16.9**	cloggy	1.33	12.2
heavy	**2.75**	**17.6**	**violent**	**5.27**	**33.3**
wide	**2.22**	**26.3**	**dry**	**1.45**	**15.3**

3. SUBJECTIVE EVALUATION EXPERIMENT IN EACH GENERATION

We carried out a subjective evaluation experiment of air conditioning sounds in a vehicle using the SD method [2] in each generation of the subjects. First, we carried out an audibility test to investigate the audibility characteristics of each generation. And then, we carried out a subjective evaluation experiment using the evaluation words selected in Sec. 2.3.

3.1. Investigation of audibility of subjects

In this experiment, there are subjects in various generations. It is thought that the feelings of the air-conditioning sounds are depended on their individual audibility. Therefore, it is necessary to perform an audibility test in each subject.

We presented various pure tones to each subject via headphones in a soundproof room. The frequencies of pure tones were 125, 250, 500, 1000, 2000, 4000, and 8000 Hz. We changed the sound pressure level (SPL) of each pure tone from -10 dB to 40 dB at a step of 2.5 dB and recorded the absolute threshold of hearing at each test.

48 subjects who had normal hearing acuity participated in the experiment. Table 2 shows the number of the subjects in each generation.

Table 2: Number of subjects in each generation.

generations	20s	30s	40s	50s
The number of subjects	13	12	12	11

Figure 2 shows the average value of the absolute threshold of hearing in each generation. In Fig. 2, the absolute thresholds of hearing below 1000 Hz and above 2000 Hz rise as the generation increase, i.e., the audibility declined at lower and higher frequencies in the higher generation.

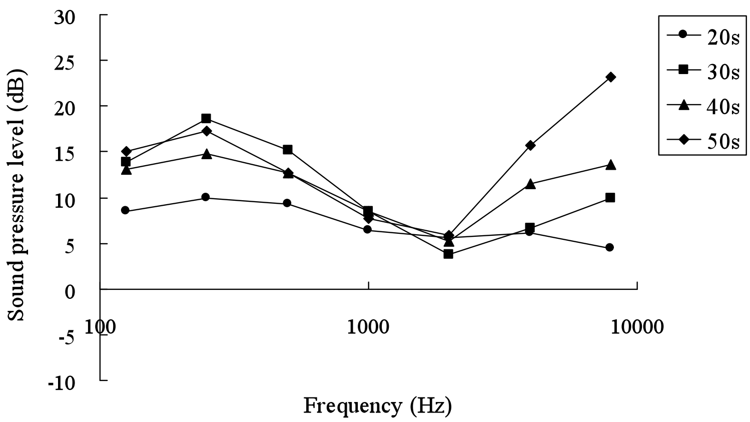

Figure 2: Absolute thresholds of hearing in each generation. Each symbol denotes an average value over both ears in each generation.

3.2. Subjective evaluation experiment

We tried to evaluate the air-conditioning sounds using SPL and psychoacoustic parameters of the loudness and sharpness. There is, however, a strong correlation between the loudness and sharpness in an experiment (correlation coefficient = 0.88) reported previously [6]. It is, therefore, necessary to investigate effects of respective changes in the loudness and sharpness on each evaluation word. Then, we carried out a subjective evaluation experiment using processed air-conditioning sounds that were changed in the loudness and sharpness. We selected a sample of the air-conditioning sounds from Vent mode, and processed them using an equalizer. We changed the loudness and sharpness of the sample sound with reducing or enlarging its SPL on each auditory critical band. We changed the loudness from 11 to 23 sone at a step of 3 sone, and changed the sharpness from 0.8 to 2.0 acum at a step of 0.3 acum. Then, we produced 30 processed sounds that have six patterns of the loudness and five patterns of the sharpness on Vent mode in total. The processed sounds were presented to the subjects through headphones in a soundproof room. In the experiment, we added two words of "warm" and "cool" as the evaluation words of thermal feeling for air-conditioning sounds besides seven evaluation words obtained from Sec. 2.3. After each presentation, we asked the subjects to evaluate image of each sound in seven degrees (0 to 6 points) for each evaluation word.

3.3. Results

3.3.1. Evaluation using SPL and loudness

In the results of the experiment, there are strong correlations between the evaluation score and the SPL in the words of "violent" and "quiet." Figure 3 shows the relationships between the evaluation score of "violent" and the SPL at sharpnesses of 0.8, 1.4, and 2.0 acum. In Fig. 3, the gaps of the evaluation scores among the generations become marked as the sharpness increases. When the generation become lower, the dependence of the score on the SPL becomes large. These results show that the lower generation subjects were more sensitive for the loudness of the air-conditioning sound than the higher generation subjects. Figure 4 shows the relationships between the evaluation score of "violent" and the loudness at sharpnesses of 0.8, 1.4, and 2.0 acum. Comparing Fig. 4 with Fig. 3, the general tendency is almost the same. This result shows that the loudness of air-conditioning sound could be evaluated enough using the SPL.

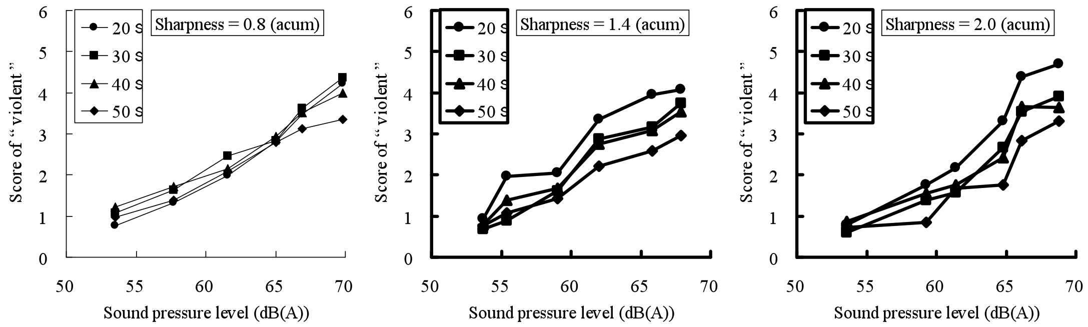

Figure 3: Relationship between the evaluation score of "violent" and the SPL (sharpness = 0.8, 1.4, 2.0 (acum)).

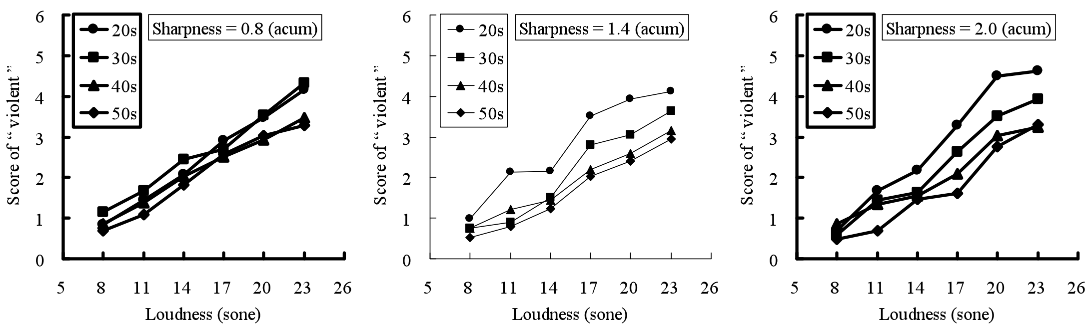

Figure 4: Relationship between the evaluation score of "violent" and the loudness (sharpness = 0.8, 1.4, 2.0 (acum)).

3.3.2. Evaluation using sharpness

Figure 5 shows the evaluation scores of "heavy" and "wide" depending on the sharpness at a loudness of 14 sone. These evaluation scores of "heavy" and "wide" were correlated with the sharpness and were little correlated with the loudness on the previous report [6]. Tendencies of these correlations in the experiment are almost the same as the previous report. In differences among the generations, the generation becomes higher, the dependence of the evaluation score on the sharpness becomes lower. Considering the results of audibility tests, in the higher generation subjects whose audibility had been declined at the lower and higher frequencies described in Sec. 3.1, it is thought that the sharpness of the air-conditioning sound was difficult to be evaluated.

Figure 6 shows the evaluation scores of "warm" and "cool" depending on the sharpness at a loudness of 11 sone. In both cases of "warm" and "cool," dependencies of the evaluation scores on the sharpness increase as the generation becomes lower. This result shows that the lower generation subjects were sensitive for the thermal feeling of the air-conditioning sounds that changed depending on the sharpness. It could be, therefore, expected that a synergy effect for the heating or cooling performance that is emphasized by controlling the sharpness of the air-conditioning sound.

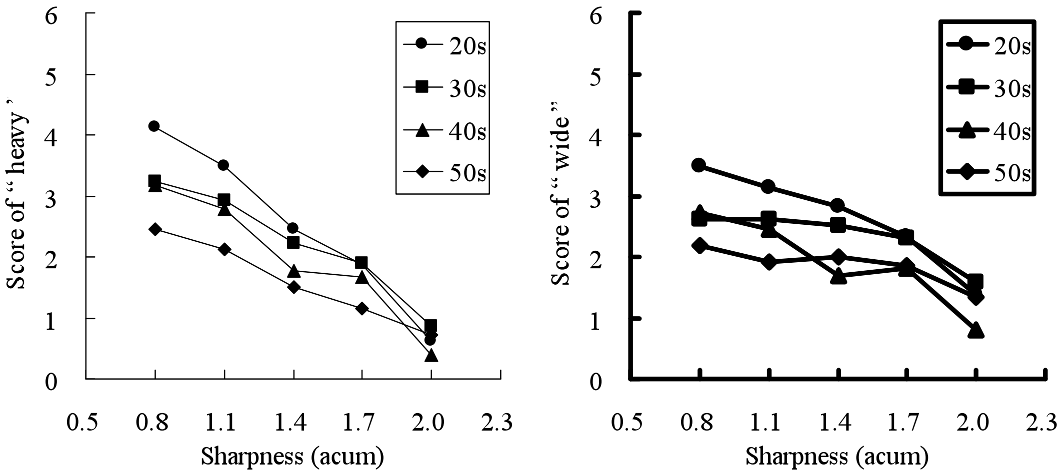

Figure 5: Evaluation scores of "heavy" and "wide" depending on the sharpness (loudness = 14 sone).

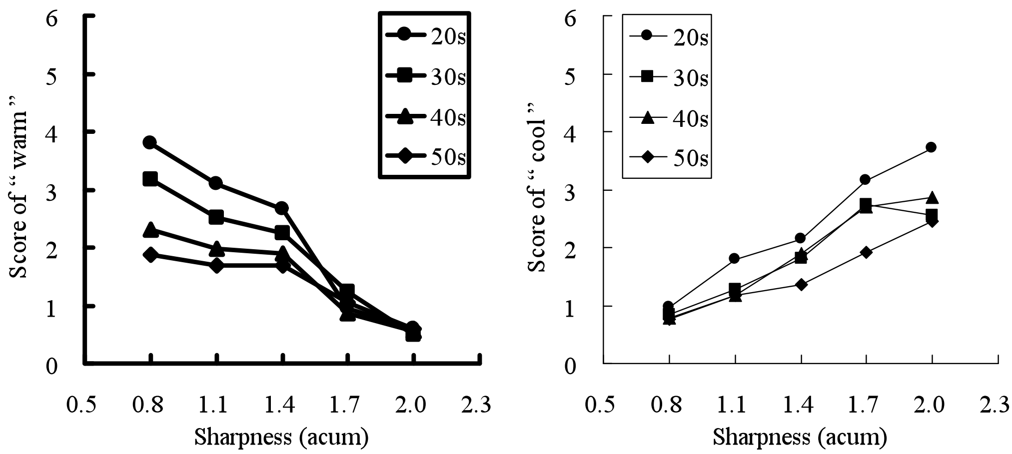

Figure 6: Evaluation scores of "warm" and "cool" depending on the sharpness (loudness = 11 sone).

4. FACTOR ANALYSIS

We performed a factor analysis to the experimental data in each generation. In this analysis, noting that it is able to explain the air-conditioning sound more than 90% of the all evaluation words until the second factor. Therefore, we extracted two factors in this analysis. Tables 3 and 4 show the contribution ratios and the factor loadings for the extracted factor in each generation, respectively.

In each generation, about the words of "heavy," "cool," "warm," "wide," and "dry," their absolute values of factor loadings for the factor 1 are high. About words of "violent," "quiet" and "muddy," the absolute values of factor loadings for the factor 2 are high. Therefore, we defined the factor 1 and 2 as "thermal factor" and "rough factor," respectively. In Table 3, noting that the contribution ratio for the factor 1, i.e. "thermal factor," decreases as the generation becomes higher. Conversely, the contribution ratio for the factor 2, i.e. "rough factor," increases. As a result, considering that the lower generation subjects mainly evaluated the air-conditioning sound by the thermal factor. On the other hand, in the higher generation subjects, the weight of the evaluation decreased on the thermal factor and increased on the rough factor.

Figure *7* shows the relationship between the psychoacoustic parameters and the extracted factors. As results, the thermal factor has a strong correlation with the sharpness (correlation coefficient = -0.97), and the rough factor has a strong correlation with the loudness (correlation coefficient = 0.99).

Table 3: Contribution ratio on the extracted factor.

Factor	Contribution ratio (%)			
	20s	30s	40s	50s
1	63.9	56.7	60.0	50.2
2	31.5	35.6	34.1	41.7
Total	95.4	92.4	94.0	91.9

Table 4: Factor loadings for extracted factors.

evaluation word	20s Factor		30s Factor		40s Factor		50s Factor	
	1	2	1	2	1	2	1	2
heavy	**0.994**	0.064	**0.965**	0.258	**0.983**	0.154	**0.981**	0.033
cool	**-0.994**	-0.013	**-0.962**	-0.125	**-0.967**	-0.168	**-0.966**	-0.197
warm	**0.977**	-0.156	**0.984**	-0.132	**0.950**	-0.233	**0.902**	-0.387
wide	**0.958**	0.175	**0.752**	0.407	**0.944**	0.186	**0.877**	0.017
dry	**-0.933**	-0.232	**-0.798**	-0.500	**-0.880**	-0.390	**-0.775**	-0.505
refreshing	**-0.935**	0.296	**-0.899**	0.354	**-0.927**	0.244	-0.578	**0.757**
violent	-0.123	**0.986**	0.017	**0.990**	-0.010	**0.978**	0.045	**0.990**
quiet	0.120	**-0.972**	0.089	**-0.970**	0.064	**-0.979**	0.017	**-0.965**
muddy	0.358	**0.846**	0.513	**0.805**	0.258	**0.895**	0.324	**0.906**

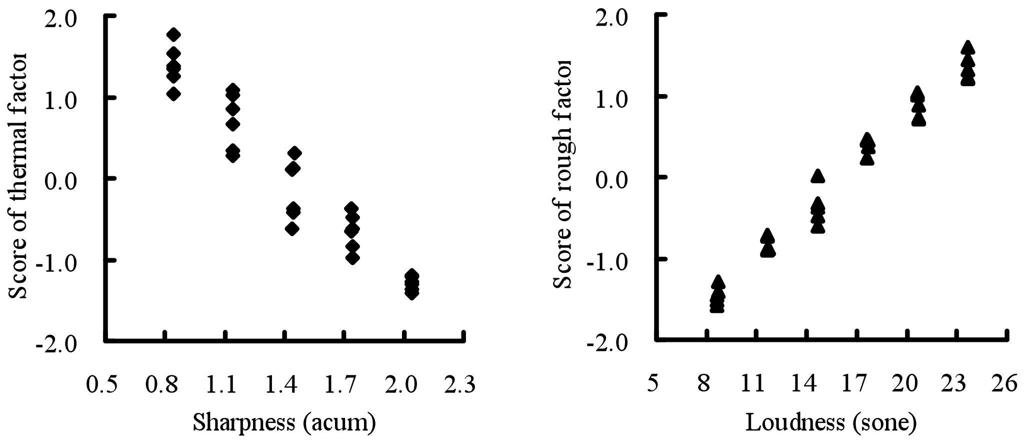

Figure 7: Relationship between the psychoacoustic parameters and the extracted factors.

5. CONCLUSION

We tried to evaluate air-conditioning sounds in a vehicle from a viewpoint of sound quality for various generation subjects. First, we selected seven evaluation words of "quiet," "refreshing," "heavy," "wide," "muddy," "violent," and "dry" that represent characteristics of the sounds. Next, we carried out a subjective evaluation experiment for the air-conditioning sounds in each generation by means of the SD method using the previous seven evaluation words and two of "warm" and "cool" as words that represent thermal feelings of the sounds. As a result, there were similar tendencies between the evaluation results of the SPL and of the loudness, therefore, considering that the loudness of the air-conditioning sound could be evaluated enough by using the SPL. And there were differences among generations on the evaluation results of the SPL and loudness, noting that the lower generation subjects were more sensitive to evaluate the air-conditioning sound by the SPL and loudness. About the evaluation results using the sharpness, there were differences among the generations, and noting that the dependences of the evaluation scores of "warm" and "cool" for the sharpness became increase as the generation became lower. It could be, therefore, expected that a synergy effect for the heating or cooling performance that is emphasized by controlling the sharpness of the air-conditioning sound for the lower generation. Finally, we performed a factor analysis and extracted two factors of "thermal factor" and "rough factor." The thermal factor had a strong correlation with the sharpness, and the rough factor had a strong correlation with the loudness. From this analysis, noting that the lower generation subjects mainly evaluated the sharpness of the air-conditioning sound, and the higher generation subjects evaluated not only the sharpness but also the loudness because the weight of the evaluation on the loudness increased when the generation became higher. Therefore, it is important to control the sharpness of the air-conditioning sound for the lower generations, and to decrease the loudness for the higher generations.

REFERENCES

1. S. Kuwano: Psychological evaluation of sound quality of machinery noise, J. Acoust. Soc. Jpn. 53, No.6 456-461, 1997.
2. S.Namba and S. Kuwano: Method of Psychological Measurement for hearing research, Corona publishing, Tokyo, pp. 107-131, 1998.
3. S. Kuwano, F. Hugo, S. Namba, S. Nakamura, and H. Uchida: Psychological evaluation of door sound of cars in relation to the class of cars, Proc. of spring meeting of ASJ. 1-7-8, 745-746, 2002.
4. K. Abe, K. Ozawa, Y. Suzuki, and T. Sone: Evaluation of environmental sounds using adjectives describing sound quality, emotional state, and information carried by sound, J. Acoust. Soc. Jpn. 54, No.5 343-350, 1997.
5. Paul. G. Hoel: Elementary Statistics, Baifukan, Tokyo, 191-216, 1981.
6. R. Nakasaki, T. Ogata, Y. Ozeki, M. Onda, H. Hasegawa and M. Kasuga: Sound quality evaluation of air-conditioning sounds in a vehicle using psychoacoustic parameters, Proc. of Acoustics '08 Paris, 3805-3810, 2008.