Sound quality evaluation of air-conditioning sounds in a vehicle using psychoacoustic parameters

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In this study, we tried to evaluate the air-conditioning sounds in a vehicle from a viewpoint of sound quality. First, we carried out an experiment to select suitable words that represent images of the air-conditioning sounds. As a result, seven words of “quiet, ” “refreshing, ” “heavy, ” “wide, ” “muddy, ” “violent,” and “dry” were selected as the evaluation words of the air-conditioning sounds. Next, we carried out a subjective evaluation experiment using the seven evaluation words. As a result of the factor analysis, noting that the air-conditioning sounds can be explained by three factors of “rough,” “space” and “refreshing.” “Rough” factor has strong correlation with SPL (sound pressure level) of the air-conditioning sounds, however, the factors of “space” and “refreshing” have little correlation with the SPL. Finally, to investigate parameters that correlate with these factors, we carried out an experiment to evaluate the air-conditioning sounds using the psychoacoustic parameters of loudness and sharpness. As results, noting that “rough” factor strongly correlates with the loudness, “space” and “refreshing” factors correlate with the sharpness. These results show that it is possible to evaluate the air-conditioning sounds from a viewpoint of sound quality by using the psychoacoustic parameter of sharpness.

1 Introduction

With a recent development of technologies to reduce noises from mechanical components of a vehicle, quietness in the compartment of a vehicle is improved 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 the sound pressure level (SPL), and many countermeasures are done to reduce the SPL of the sounds. However, it takes much cost to reduce the SPL of the sounds. And recently, sound quality of air-conditioning sounds become important. 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 for sounds in various air-conditioning modes, and performed a factor analysis to determine major factors that represent characteristics of the air-conditioning sounds. Finally, we carried out an experiment to investigate which psychoacoustic parameters such as loudness and sharpness are correlated with the evaluation words that represent 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 Measurement conditions

In a vehicle, users can set the air-conditioning mode freely depending on season, temperature, and purpose. 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. The conditions of the air inlet and outlet on each air-conditioning mode are shown in Fig.1. And 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.

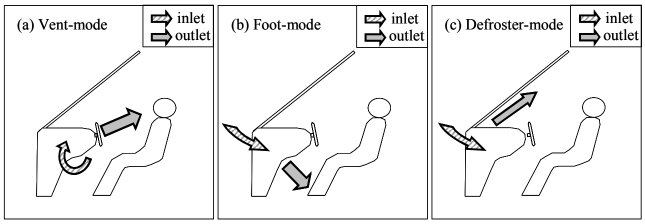


Fig.1 Air-conditioning mode (inlet and outlet).

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. 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 [2] and [3].

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

2.3 Results

We performed a cluster analysis to the data obtained from this 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 [4]:

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

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

We carried out a subjective evaluation experiment for the air-conditioning sounds by means of the SD (semantic differential) method using the seven evaluation words selected in Sec. 2.3.

3.1 Experiment conditions

The air-conditioning sounds were recorded by the same method in Sec. 2.1. In addition to the sounds at the condition of Fan-max, where the air-conditioning sounds are perceived loudest, we recorded the sounds at the condition of Fan-middle that is often used when the thermal comfort in the compartment is enough. The sounds at Fan-middle condition were recorded at Vent-mode and Foot-mode. Eleven vehicles of various classes and models were used for the measurement as shown in Table 2.

Table 2 Vehicles for the measurement.

No.	Class	Model
1	LL	Sedan
2	LL	Sedan
3	LL	Sedan
4	LL	Sedan
5	LL	Sedan
6	L	Sedan

No.	Class	Model
7	M	Minivan
8	S	Hatchback
9	S	Sedan
10	SS	Hatchback
11	SS	Hatchback

3.2 Subjective evaluation experiment using SD method

The air-conditioning sounds at the five modes of Vent-max, Foot-max, Defroster-max, Vent-middle, and Foot-middle in each vehicle were presented to the subjects through headphones in a soundproof room (D-30). The SPL of each air-conditioning sound was adjusted to the same level (from 45dB(A) to 70 dB(A) at Fan-max and Fan-middle) in the vehicle compartment. After each presentation, we asked the subjects to evaluate image of each presented sound in seven degrees (0 to 6 points) for each evaluation word selected in Sec. 2.3.

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

3.3 Results of factor analysis

There are several methods for factor analysis, in this study, we employed the principal factor method to extract major factors of the air-conditioning sounds. The cumulative contribution ratios by the factor analysis are shown in Table 3.

Table 3 Cumulative contribution ratios.

Factor	Primary eigenvalue		
	Total	Variance ratio (%)	Cumulative contribution ratio (%)
1	2.54	36.24	**36.24**
2	1.89	26.98	**63.23**
3	0.95	13.61	**76.83**
4	0.60	8.64	85.47
5	0.45	6.47	91.95
6	0.34	4.79	96.74
7	0.23	3.26	100.00

From the cumulative contribution ratios in Table 3, noting that it is able to explain the air-conditioning sounds more than 75% of the all evaluation words until the third factor. Therefore, we extracted three factors in this experiment. Table 4 shows the factor matrix of the post-varimax rotation [5]. This table presents the factor loadings of each evaluation word for the three extracted factors.

Table 4 Factor matrix.

Adjective	Factor		
	1	2	3
violent	0.89	0.22	-0.08
dry	0.71	-0.02	0.12
quiet	-0.64	0.08	0.45
muddy	0.49	0.39	-0.04
heavy	0.05	0.96	0.07
wide	0.09	0.54	0.41
refreshing	-0.03	0.10	0.72

About four words of "violent," "dry," "quiet," and "muddy," their absolute values of factor loadings for the factor 1 are high. About words of "heavy" and "wide," the absolute values of factor loadings for the factor 2 are high.

And about the word "refreshing," the absolute value of factor loading for the factor 3 is high. Therefore, we defined the factor 1 as "rough factor," the factor 2 as "space factor," and the factor 3 as "refreshing factor."

4 Discussion

Here, we discuss the relationships between the sound pressure level (SPL dB(A)) of the air-conditioning sounds and factors extracted in Sec. 3.3.

4.1 Rough factor

The relationship between the rough factor and the SPL (dB(A)) is shown in Fig. 2.

In Fig. 2, the factor score becomes large as the SPL increases, and a strong correlation (correlation coefficient = 0.97) is indicated between them. This result shows that the evaluation words of "violent," "dry," "quiet" and "muddy" strongly relate to the SPL. Therefore, the images of these words can be improved to reduce the SPL. It is also shown that the subjects hardly had the rough image to the air-conditional sounds at a level of under 60 dB(A), since the factor score becomes negative when the SPL is less than 60 dB(A).

4.2 Space factor and refreshing factor

The relationships between the space factor and the SPL (dB(A)) and between the refreshing factor and the SPL (dB(A)) are shown in Fig. 3 and Fig. 4, respectively.

There is little correlation between the space factor and the SPL in Fig. 3. (correlation coefficient = −0.03) This result shows that the space factor represents characteristics of the air-conditioning sounds that different from the SPL.

In Fig. 4, the refreshing factor score becomes large as the SPL decreases. The correlation between the refreshing factor and the SPL is high (correlation coefficient = 0.72). Since, however, dependence of the refreshing factor on the SPL is weak, it is not expectable to improve the refreshing image greatly by reducing the SPL.

4.3 Relationship between space factor and refreshing factor

We show the relationship between the space and refreshing factors in Fig. 5.There is a negative correlation between the space and refreshing factors (correlation coefficient = 0.59). From a viewpoint of comfortableness of the air-conditioning sounds, if there is a negative correlation between the comfortableness and the space factor score, the users gradually feel comfortable as the score decreases. Conversely, if there is a positive correlation between the comfortableness and the space factor, the balance between the space and refreshing factors becomes important to improve the comfortableness. And it is necessary to investigate indicators that correlate with these factors.

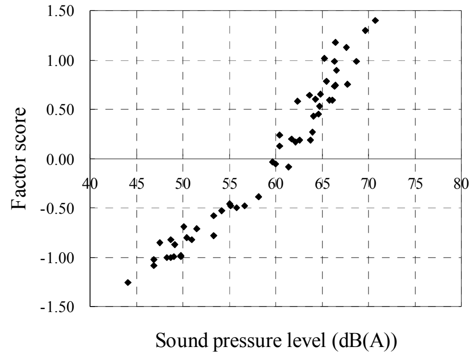


Fig. 2 Rough factor *vs.* SPL (dB(A)).

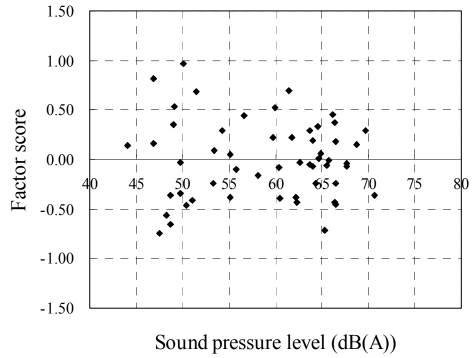


Fig. 3 Space factor *vs.* SPL (dB(A)).

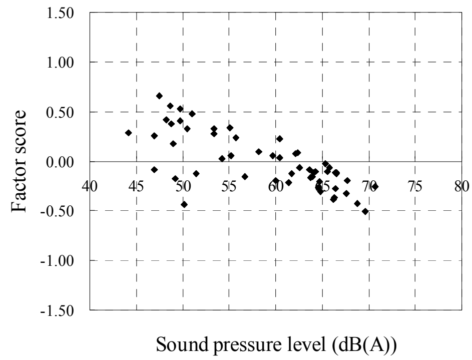


Fig. 4 Refreshing factor *vs.* SPL (dB(A)).

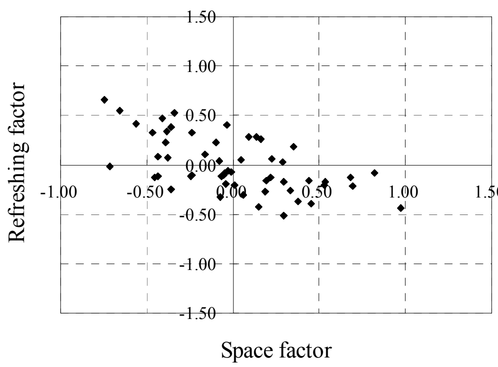


Fig. 5 Relationship between the space factor and the refreshing factor.

5 Subjective evaluation using psychoacoustic parameters

In this section, we investigated the relationship between the evaluation words representing characteristics of the air-conditioning sounds and the psychoacoustic parameters of loudness and sharpness.

5.1 Psychoacoustic parameters

We used the parameters of loudness and sharpness to evaluate the air-conditioning sounds. Loudness is a subjective measure of the sound pressure, and it is standardized in ISO 532B. On the other hand, sharpness is not yet standardized, and researches for standardization are pushed forward now. Sharpness S is calculated based on the loudness of sound by the following equation:

$$S = 0.11 \frac{\int_0^{24\,Bark} N' g'(z) z\, dz}{\int_0^{24\,Bark} N' dz}, \qquad (2)$$

where N' is the specific loudness, z is the number of the auditory critical band, and $g'(z)$ is the weighting coefficient that depends on the number of the auditory critical band [6].

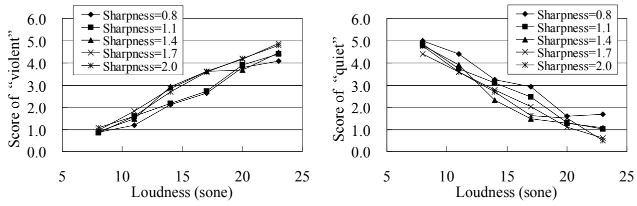
5.2 Subjective evaluation experiment using processed sounds

We tried to evaluate the results of the previous experiment using the psychoacoustic parameters of loudness and sharpness. However, there is a strong correlation between the loudness and sharpness (correlation coefficient = 0.88). It is, therefore, necessary to investigate effects of respective changes in the loudness and sharpness on each evaluation word. To investigate effects of respective changes in the psychoacoustic parameters, 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 air-conditioning sounds from each mode, and processed them by using an equalizer. We changed the loudness and sharpness of the sounds with reducing or enlarging the SPL of each auditory critical band. We changed loudness from 11 to 26 (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 made 30 sounds that have six patterns of loudness and five patterns of sharpness on each mode, in total there were 90 processed samples of the air-conditioning sounds. The processed sounds were presented to the subjects through headphones in a soundproof room (D-30). In this experiment, besides seven evaluation words obtained from Sec. 2.3, we added three words of "warm," "cool" and "luxury" as the evaluation words of air-conditioning sounds to investigate the space and refreshing factors further. After each presentation, we asked the subjects to evaluate image of each sound in seven degrees (0 to 6 points) for each evaluation word.

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

5.3 Relations between the evaluation words and psychoacoustic parameters

The relationships between the evaluation words of "violent," "quiet" and loudness on Vent mode are shown in Fig. 6.

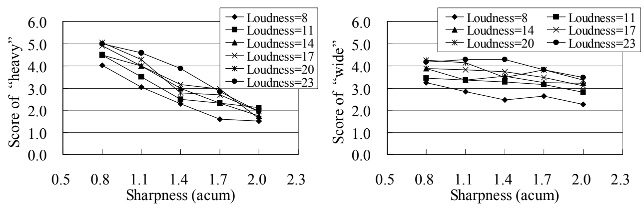


(a) Violent (b) Quiet

Fig. 6 Relationship between the words ("violet" and "quiet") that constitute the rough factor and loudness on Vent mode.

The results of Fig. 6 show that the loudness have strong relations with the word of "violent" and "quiet" that constitute the rough factor. The relation between the loudness and these words has the same tendency as the relation between the SPL and the ones. In other word, it can be considered that the loudness has a strong relation with the rough factor.

The relationship between the words of "heavy" and "wide" that constitute the space factor and sharpness are shown in Fig. 7.

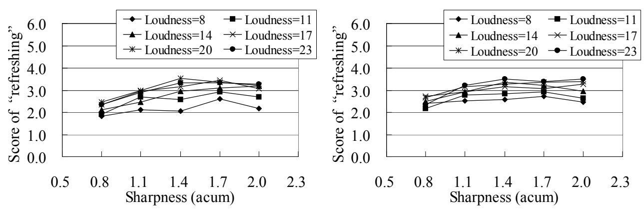


(a) Heavy (b) Wide

Fig.7 Relationship between the words ("heavy" and "wide") that constitute the space factor and sharpness on Foot mode.

From Fig. 7, it can be considered that the space factor has a negative correlation with sharpness.

The relationship between the words of "refreshing" that constitutes the refreshing factor and sharpness are shown in Fig. 8.

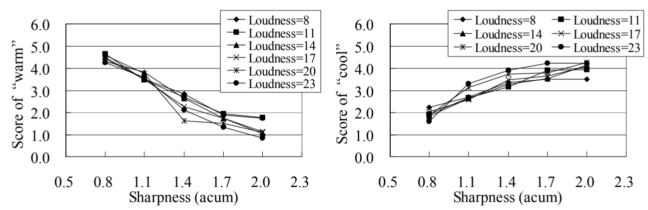


(a) Refreshing (Foot mode) (b) Refreshing (Vent mode)

Fig. 8 Relationship between the word of "refreshing" and sharpness on Foot and Vent modes.

From Fig. 8, it can be considered that the refreshing factor has a weak positive correlation with sharpness.

The relationship between the words of "warm," "cool" and sharpness is shown in Fig. 9.



(a) Warm (Foot mode) (b) Cool (Vent mode)

Fig. 9 Relationship between the words ("warm" and "cool") that represent the temperature and sharpness.

In Fig. 9, the word of "warm" has a negative correlation with sharpness, on the other hand, the word of "cool" has a positive correlation with sharpness. Therefore, it can be considered the sound characteristics that represent the images of temperature depend on the sharpness. From the above, on Foot mode that is required warmth, reducing the sharpness is effective to improve the sound quality. And on Vent mode that is required coolness, enlarging the sharpness is effective to improve the sound. Using the sharpness for sound quality evaluation, a synergy effect can be expected to the improvement for the air-conditioning thermal performance. But, in a case of the sharpness is too high or too low, the users may feel uncomfortable. It is important, therefore, to consider a balance of the sharpness.

5.4 The correlation between the evaluation words

The correlation coefficients among the evaluation words are shown in Table 5. There are strong correlations among "warm," "heavy," and "luxury" each other. These words have negative correlations with the sharpness, therefore, images of the air-conditioning sounds about these words can be improved to control the low frequency component of the sounds.

There are strong correlations among "cool," "dry," and "refreshing" each other. These words have positive correlations with the sharpness, therefore, images of the sounds about these words can be improved to control the high frequency component of the sounds.

It is effective for evaluation of the air-conditioning sound using not only its SPL but also its sharpness.

Table 5 Correlation between the evaluation words.

positive correlation
negative correlation

	heavy	quiet	dry	refreshing	muddy	violent	wide	warm	cool	luxury
heavy		-0.06	**-0.84**	-0.46	-0.22	0.04	0.75	**0.89**	**-0.86**	0.79
quiet			-0.46	-0.70	**-0.82**	**-0.98**	-0.61	0.38	-0.37	0.50
dry				0.74	0.65	0.48	-0.35	**-0.98**	**0.95**	**-0.96**
refreshing					0.63	0.69	0.16	-0.74	**0.80**	-0.72
muddy						**0.83**	0.28	-0.58	0.55	-0.69
violent							0.59	-0.40	0.39	-0.52
wide								0.42	-0.37	0.31
warm									**-0.97**	**0.96**
cool										**-0.92**
luxury										

6 Conclusion

We tried to evaluate air-conditioning sounds in a vehicle from a viewpoint of sound quality. First, we selected seven evaluation words of "quiet," "refreshing," "heavy," "wide," "muddy," "violent," and "dry" as the evaluation words that represent characteristics of the sounds. Next, we carried out a subjective evaluation experiment for the sounds by means of the SD method using the seven evaluation words and performed a factor analysis. As a result, the air-conditioning sounds can be represented as the following three factors: "rough" factor that related to the evaluation words of "violent," "dry," "quiet," and "muddy," "space" factor that related to "heavy" and "wide," and "refreshing" factor that related to "refreshing." We discussed relationships among the three extracted factors and the SPL of the sounds. As results, noting that the rough factor strongly correlated with the SPL, the space factor hardly correlated with the SPL, the refreshing factor correlated with the SPL, and a negative correlation was observed between the space and refreshing factors. Finally, we investigated relationships between the evaluation words and psychoacoustic parameters of the loudness and sharpness. As results, noting that the words that constituted the rough factor strongly correlated with the loudness, and the words that constituted the space factor had weak negative correlations with sharpness, and the word that constituted the refreshing factor had a positive correlation with the sharpness. The words of "warm" and "cool" that represent the thermal temperature sensation also had correlations with sharpness. Therefore, controlling the sharpness for the air-conditioning mode, it is expectable to get a synergy effect with the thermal performance of the air-conditioning system. By using the sharpness, it is possible to improve the sound quality of the air-conditioning sounds that is a different viewpoint from the SPL.

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