Evaluation of air-conditioning sounds in a vehicle to determine thermal feelings using psychoacoustic parameters

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Abstract: In this paper, we investigated subjective impressions of air-conditioning sounds in a vehicle by using the psychoacoustic parameters of loudness and sharpness. First, we carried out a subjective evaluation using a rating scale method and investigated the relationships between the psychoacoustic parameters and nine evaluation words, quiet, refreshing, heavy, wide, muddy, violent, dry, warm, and cool, that represent impressions of air-conditioning sounds. As a result, we found that the impressions of “violent” and “quiet” strongly depended on the loudness, and the impressions of “heavy,” “dry,” “warm,” and “cool” strongly depended on the sharpness. Next, we performed a factor analysis. As a result, we found that the air-conditioning sounds can be explained by two factors, a volume factor and a thermal factor, which were strongly correlated with the loudness and sharpness, respectively. This result shows that the feelings of heating and cooling perceived from air-conditioning sounds are related to the sharpness. Therefore, a synergetic effect on the heating and cooling performance can be expected by improving the sharpness of air-conditioning sounds.

Keywords: Air-conditioning sound, Sound quality, Subjective evaluation, Psychoacoustic parameter, Thermal feelings

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1. INTRODUCTION

The development and popularization of hybrid vehicles, electric vehicles, and fuel cell vehicles have advanced rapidly. It is generally known that the noise originating from the engine of these vehicles is considerably reduced or eliminated compared with that from a conventional engine vehicle. With the reduction of engine noise, various other noises heard in the compartment of a vehicle become more obvious such as road noise, airflow noise, air-conditioning noise, and so on. In particular, air-conditioning sounds are easily perceived as noise because they are discharged directly to the compartment. This may result in the possibility of discomfort of the driver. Therefore, the further reduction of airflow sounds from the air-conditioning system is required. There are, however, many restrictions and issues that make it more difficult to reduce air-conditioning sounds such as the cost of countermeasures against the noise, the layout of the air ducts around the air-conditioning system, and the negative impact on the air-conditioning performance caused by the countermeasures. Therefore, not only should the sounds from the air-conditioning system be reduced but also the remaining sound should induce comfortable feelings in the driver.

We previously reported the results of subjective evaluations of air-conditioning sounds in the compartment of a vehicle [1–3]. In these reports, we extracted seven words, quiet, refreshing, heavy, wide, muddy, violent, and dry, that can be used to evaluate air-conditioning sounds and showed that air-conditioning sounds can be represented by three factors, rough, space, and refreshing. The “rough” factor had a strong correlation and a dependence on the SPL (sound pressure level). The “space” and “refreshing” factors, however, had little dependence on the SPL. This result showed that these factors represented sound characteristics that could not be evaluated by the SPL only. It is therefore necessary to evaluate these factors from viewpoints other than the SPL.

In this paper, we evaluated air-conditioning sounds by using the psychoacoustic parameters of loudness and sharpness. First, we carried out a subjective evaluation
using a rating scale method. In addition to the above-mentioned seven evaluation words, we added two words, warm and cool, representing thermal feelings, which are important performances for an air-conditioning system, and investigated the relationships between the characteristics of air-conditioning sounds and thermal feelings. Next, we performed a factor analysis to determine major factors that represent the characteristics of air-conditioning sounds and investigated the relationships between the extracted factors and the psychoacoustic parameters.

2. SUBJECTIVE EVALUATION USING RATING SCALE METHOD

2.1. Recording of Air-conditioning Sounds

In a vehicle, the air-conditioning system has some air outlets, and the air outlets depend the air-conditioning mode such as “Vent mode,” “Foot mode,” and “Defroster mode.” Users can set the air-conditioning mode freely depending on the season, temperature, and purpose.

“Vent mode” is mainly used in summer and frequently used when the user wants to lower the temperature in the compartment. In this mode, the airflow is toward the face of the user. “Foot mode” is mainly used in winter and frequently used when the user wants to raise the temperature in the compartment. In this mode, the airflow is toward the feet of the user. “Defroster mode” is used when the window becomes clouded. In this mode, the airflow is toward the windshield. In this evaluation, we employed air-conditioning sounds in the above three representative modes. We set each mode to “Fan-max,” where the fan rotates at the maximum speed and the air-conditioning sound was perceived to be the loudest. For the temperature setting, we set “Cold-max” in the Vent mode and “Hot-max” in the Foot mode and Defroster mode. In the air inlet to the compartment, the air is recirculated in the Vent mode but is introduced from outside the compartment in the Foot mode and Defroster mode. The airflow for each mode is shown in Fig. 1.

To record the air-conditioning sounds for the evaluation, we selected a vehicle whose air-conditioning sounds have no unusual sounds in audible frequency bands in all air-conditioning modes. We recorded the air-conditioning sounds of the vehicle in a soundproof room where the ambient background noise was under 40 dB(A). In the recording, the engine of the vehicle was idling. We received the air-conditioning sounds using two nondirectional microphones that were installed at the ear positions of the driver and binaurally recorded the sounds onto a digital audio tape (Sony TCD-D8, sampling frequency: 48 kHz).

2.2. Preparation of Presentation Sounds

As described in the previous section, we recorded air-conditioning sounds of a vehicle in three representative modes onto a digital audio tape. These sounds were presented to a dummy head (HEAD acoustics) through headphones (Sennheiser HD-595) and calibrated to the level during the recording in the compartment. We processed these recorded sounds using an equalizer (Muller-BBM, PAK-system), and varied the loudness and sharpness of the sounds by reducing or increasing the SPL in each auditory critical band. We employed six loudnesses of 8, 11, 14, 17, 20, and 23 (sone) and five sharpnesses of 0.8, 1.1, 1.4, 1.7, and 2.0 (acum), because most of the air-conditioning sounds are fitted within these ranges. Figure 2 shows the frequency characteristics of the processed sounds in the Vent mode for a loudness of 14 (sone).
2.3. Loudness and Sharpness Models

We used the psychoacoustic parameters of loudness and sharpness to evaluate the air-conditioning sounds. We adopted the loudness model that is standardized in ISO 532B [4]. On the other hand, sharpness has not yet been standardized, and we adopted the sharpness model described as follows. The sharpness $S$ is calculated from the loudness of a sound using

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

where $N'$ is the specific loudness, $z$ is the number of auditory critical bands, and $g'(z)$ is the weighting coefficient, which depends on the number of auditory critical bands [5].

2.4. Experimental Method

We carried out the subjective evaluation of the air-conditioning sounds using a rating scale method [6] with the nine evaluation words “violent,” “quiet,” “heavy,” “wide,” “muddy,” “dry,” “refreshing,” “warm,” and “cool.” In [1–3], the seven words “violent,” “quiet,” “heavy,” “wide,” “muddy,” “dry,” and “refreshing,” were extracted as words for evaluating air-conditioning sounds from the list of 120 adjectives referred to in [7–10]. We added the two words “warm” and “cool” to represent thermal feelings because the comfort performances of heating and cooling are important for air-conditioning systems. We here investigated the relationships between the thermal feelings and the characteristics of air-conditioning sounds that can be represented by the psychoacoustic parameters of loudness and sharpness.

Twelve subjects (two females and ten males) in their 20's, who had normal hearing acuity, participated in the experiment. The processed sounds obtained in Sect. 2.2. were presented one by one to the subjects through headphones (Sennheiser HD-595) in a soundproof room (D-30). The subjects were informed in advance that they were evaluating air-conditioning sounds. The presentation sequence of the processed sounds is shown in Fig. 3. In the test, each air-conditioning sound was presented to the subject three times. After the presentation, subjects were given 30 seconds to evaluate their impressions of the air-conditioning sound, which was followed immediately by the next sound. In the evaluation, we asked the subjects to evaluate each presented sound using a seven-point scale (0 to 6 points; 0: not at all, 2: not very, 4: fairly, 6: very) for each evaluation word. Fifteen tests were carried out in a session; we carried out six sessions to evaluate all 90 sample sounds. These six sessions were randomly repeated four times. Therefore, each subject evaluated 360 sounds (15 tests × 6 sessions × 4 repeats), and, in total, the 12 subjects evaluated 4,320 sounds. Subjects participated in no more than two sessions in a day, and the interval between the sessions of each subject was more than two hours.

3. RESULTS OF SUBJECTIVE EVALUATION

3.1. Relationships between Evaluation Score and SPL

Figures 4–6 show the relationships between the average evaluation scores of all subjects and the SPL of the air-conditioning sounds for the nine different words. Figure 4 shows that the impression of “violent” becomes stronger and the impression of “quiet” becomes weaker as the SPL increases. This means that the evaluation scores of these words have strong correlations with the SPL, and the rates of change of the scores with respect to the SPL are high, i.e., the impressions of “violent” and “quiet” are sensitive to the SPL of sounds. In other words, these impressions of the sound can be improved markedly by reducing the SPL. Figure 5 shows that the impressions of “muddy,” “wide,” and “refreshing” hardly change as the SPL increases. The evaluation scores of these words have high correlations
with the SPL. However, the rates of change of the scores with respect to the SPL are low, i.e., these impressions are insensitive to the SPL, meaning that a marked improvement of these impressions cannot be expected by simply reducing the SPL. Figure 6 indicates that the evaluation scores of “dry,” “heavy,” “warm,” and “cool” have no correlation with the SPL. These impressions, therefore, cannot be evaluated by the SPL. Thus, it is difficult to improve the sound impressions shown in Figs. 5 and 6 only by using the SPL. To investigate further, we evaluate the air-conditioning sounds by using not SPL but the psychoacoustic parameters of loudness and sharpness, as described in the next section.

In the above results, the evaluation scores in the Defroster mode are similar to those in the Foot mode. We therefore omit the results for the Defroster mode in the following sections.

### 3.2. Relationships between Evaluation Scores and Loudness

Figures 7 and 8 show the dependence of the evaluation scores of “violent” and “quiet” on the loudness of the sounds, respectively. The scores of “violent” become large as the loudness increases. In contrast, the scores of “quiet” become low as the loudness increases. These tendencies are almost the same as the relationships with the SPL. These
graphs also show that the impressions of “violent” and “quiet” slightly depend on the sharpness of the sounds, because the evaluation scores slightly change by around 1 point when the sharpness changes from 0.8 (acum) to 2.0 (acum). Therefore, it is thought that a marked improvement of these impressions can be obtained by reducing the loudness or SPL but not by reducing the sharpness.

### 3.3. Relationships between Evaluation Score and Sharpness

Figures 9 and 10 show the dependence of the evaluation scores of “heavy” and “dry” on the sharpness of the sounds, respectively. The scores of “heavy” become low as the sharpness increases. In contrast, the scores of “dry” become large as the sharpness increases. These results show that these impressions can be improved by changing the sharpness of the sounds.

Figures 11–13 show the dependence of the evaluation scores of “wide,” “muddy,” and “refreshing” on the sharpness of the sounds, respectively. The score of “wide” has a negative relation with the sharpness and those of “muddy” and “refreshing” have positive relations with the sharpness. However, the sharpness dependences of these scores are weak. These results show that marked improvements for these impressions cannot be expected by simply changing the sharpness of the sounds.

### 3.4. Relationships between Thermal Feeling and Sharpness

Figures 14 and 15 show the dependence of the evaluation scores of “warm” and “cool” on the sharpness, respectively. The scores of “warm” become low as the sharpness increases. This means that the image of “warm” has a negative relation with the sharpness. It is therefore thought that there is a synergistic effect on the feeling of warmth caused by decreasing the sharpness in the Foot mode when we need to increase the compartment temperature in winter. In contrast, the scores of “cool” become large as the sharpness increases. This means that the
impression of “cool” has a positive relation with the sharpness. It is therefore thought that there is a synergetic effect on the feeling of coolness caused by increasing the sharpness in the Vent mode when we need to decrease the compartment temperature in summer.

Thus, by tuning the sharpness, synergetic effects on the heating and cooling performances can be expected. However, a concern is that extreme changes in the sharpness will cause discomfort to users. It is therefore important to consider the balance between changes in the sharpness and feeling of comfort.

4. FACTOR ANALYSIS

4.1. Extraction of Factors

We carried out factor analysis by the principal factor method to extract the major factors contributing to the impressions of air-conditioning sounds. The cumulative contribution ratios determined by factor analysis are shown in Table 1. From Table 1, the cumulative contribution ratio of the first two factors is more than 90%. We therefore extracted these two factors in this analysis. Table 2 shows the factor matrix after varimax rotation [11]. This table presents the factor loading of each evaluation word for the two extracted factors.

For the four words “heavy,” “dry,” “warm,” and “cool,” their absolute values of factor loading for factor 1 are relatively high, and for the five words “violent,” “quiet,” “wide,” “muddy,” and “refreshing,” the absolute values of factor loading for factor 2 are relatively high. Therefore, we defined factor 1 as the thermal factor and factor 2 as the volume factor.

4.2. Relationships between Psychoacoustic Parameters and Extracted Factors

Figure 16 shows the relationship between the volume factor and loudness. There is a strong correlation (correlation coefficient = 0.96) between them. This shows that the impressions of “quiet,” “violent,” “muddy,” “wide,” and “refreshing” depend on the loudness. Figure 17 shows the relationship between the thermal factor and sharpness. There is a strong correlation (correlation coefficient = 0.94) between them, that is, the impressions of “heavy,” “warm,” “cool,” and “dry” depend on the sharpness. We already found that these four words have no correlation with the SPL (see Sect. 3.1.). These impressions can therefore be evaluated by using not the SPL but the sharpness. Thus, the air-conditioning sounds are represented by two factors: the volume factor and thermal factor which have a strong correlation with loudness and sharpness, respectively. Therefore, we found that the majority of air-conditioning sounds in a vehicle can be represented by...
the two factors and can be evaluated using the loudness (or SPL) and sharpness.

5. CONCLUSION

We evaluated air-conditioning sounds in a vehicle using the psychoacoustic parameters of loudness and sharpness. First, we carried out a subjective evaluation using a rating scale method for nine evaluation words, violent, quiet, heavy, wide, dry, muddy, refreshing, warm, and cool. We found that the impressions of “violent” and “quiet” correlated strongly with the loudness. These impressions also correlated strongly with the SPL, and the tendency of the evaluation scores was similar for the SPL and loudness. We can therefore evaluate these images using only the SPL. We also found that the impressions of “heavy,” “dry,” “warm,” and “cool” correlated strongly with the sharpness. Therefore, these impressions, which include thermal feelings, can be expected to be improved by tuning the sharpness. Next, we performed a factor analysis and found that the air-conditioning sounds could be represented by the following two factors: a volume factor that was related to the evaluation words “violent,” “quiet,” “wide,” “muddy,” and “refreshing,” and a thermal factor that was related to “heavy,” “dry,” “warm,” and “cool.” The volume factor correlated strongly with the loudness, and the thermal factor correlated strongly with the sharpness. Regarding the thermal factor, the contribution ratio of the thermal factor to all the extracted factors was more than 60%. This result shows that the sharpness of air-conditioning sound is as important as the SPL, and synergistic effects on the heating and cooling performance are expected by tuning the sharpness of air-conditioning sounds.

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