The structural transfer function of each cylinder of a car engine were able to be derived by signal processing based on multiple regression analysis. On the basis of this function, combustion noise included in the engine noise was separated from the other noises such as mechanical noise. In addition, subjective evaluation experiments using this extracted combustion noise was conducted to develop a quantification method to evaluate the combustion noise. Experts of developing NVH(Noise, Vibration, Harshness) participated and Scheffe's paired comparison method was used for evaluation of the combustion noise. From the experimental results, DCNI(Dissonant Combustion Noise Index), an objective evaluation scale on sound quality using "fluctuation intensity" as a psycho-acoustic scale, was defined. However, the evaluation of general users of cars would not be the same. To discuss the consistency of this model for the experts and general users, similar subjective evaluation experiments were need to be performed. On the other hand, it would be hard to evaluate the sounds for the general users by using the word "Combustion Noise." In this study, we conducted a subjective evaluation experiment not using the technical term "combustion noise", but "engine sound" for the general users. The combustion noise evaluated and evaluation method were the same to those of the experts. As a result, the variance of evaluation values of dislike was high at almost of auditory stimuli, and the tendency did not be the same as DCNI values.

Keywords: combustion noise, subjective evaluation, difference of response

1. Introduction

Vehicle interior noise during acceleration is the mixture of various noises. One of them is the combustion noise radiated from the engine. Improving the sound quality of combustion noise is important for enhancing the attractiveness of a vehicle. The previous study[1] established the method of extracting only combustion noise from a vehicle interior noises by a digital signal processing.

In addition, a subjective evaluation experiments[2] using the extracted combustion noises was conducted to quantify the sound quality of the combustion noise. Participants were 14 engine NVH(Noise, Vibration, Harshness) development experts. Auditory stimuli were 15 types of combustion noises which obtained by previous combustion noise separation method in each three speed ranges: low-speed, mid-speed, and high-speed range.

From the experimental results, DCNI(Dissonant Combustion Noise Index) was defined as objective evaluation index on sound quality of combustion noise using “fluctuation intensity” as a psycho-acoustic metric.

However, the tendency of subjective evaluations for combustion noise by general users (they are not NVH experts but they drive production vehicle in daily life) would not be the same to those by
the experts. If the tendencies of subjective scores by general users are extremely different from them by experts, DCNI have to be matched for general users.

Therefore, we verified the tendencies of subjective scores by general users using 14 participants. In the experiment, the technical term “combustion noise” was replaced to the general term “engine noise”. The purpose of the experiment is to discuss the difference in the evaluation between NVH developing experts and general users of production car. The effectiveness of DCNI, an objective sound quality evaluation index for combustion noise, for the general users was also examined.

2. Experiment

2.1 Auditory stimuli

Auditory stimuli were the same sets of previous study[2]. From the approximately 50 types of combustion noise separated from vehicle interior noise by the time domain combustion noise separation method[1], 15 different sound quality types of combustion noise were selected for each of the three engine speed conditions: low-speed range (approx. 1500-2500 rpm), mid-speed range (approx. 3500-4500 rpm), and high-speed range (approx. 5500-6500 rpm). Using audio editing software, these signals were arranged into 2-second segments, exponentially smoothed the first and last 0.2 seconds of the signal to limit discontinuous noises. All 45 of these presentation sounds (15 types x 3 speed conditions) were saved in .wav file format to allow for audio playback on a computer.

2.2 Participants

Participants were 14 students from Utsunomiya university(13 males and 1 female), aged 21 to 24 years old. All had normal-hearing, and car driving experience.

2.3 Method

As shown in the Fig. 1(a), the participants heard the stimuli via headphone connected to audio playback system(HEAD acoustics PEQ V, HPS IV).

Scheffe’s paired comparison method[3] was used for the evaluation. The 2 stimuli were randomly selected from 15 stimuli, and these stimuli were named as sound A and B by playback order. Participants listened to the paired sounds, and then answered the question “Which engine noise is the most unpleasant?” as shown in Fig. 1(b). For example, a participant scores +2 when Sound A is the most unpleasant. The sound stimuli were paired and reproduced in 3 groups classified from the speed range. After the experiment, participants answered the criteria in introspective reports of the sound evaluated of dislike. To avoid the order effect, 15 sounds in each range were taken round-robin on each group(15 x 14 = 210 trials).

Figure 1: Experimental apparatus and answer sheet
2.4 Results

Averaged evaluated values and those of each participant for each speed range are shown in Fig. 2. For comparison, the results of evaluation on combustion noise for experts are shown in Fig. 3. The vertical axis indicates subjective scores, and the horizontal axis indicates sound numbers of each stimulus by ascending order of subjective scores for combustion noise by experts from the left, which are shown in Fig. 3. Coloured lines indicate the evaluation scores of each participant, black dots indicate those averages, and the error bars indicates the standard deviation.

![Figure 2: Subjective scores of evaluations on engine noise by general users](image1)

![Figure 3: Subjective scores of evaluations on combustion noise by experts](image2)

As shown in Figs. 2 and 3, subjective evaluation scores of general users for engine noise were varied widely in all speed ranges, compared with those of the experts for combustion noise. The evaluation tendency could not be discussed easily from these results.

To approach this issue, the clustering was applied to the obtained subjective scores of general users.
3. Analysis

3.1 Cluster Analysis

Based on the literature[4], hierarchical cluster analysis using “Ward’s method” was applied to the subjective scores of each speed range to group the participants according to the similarity of evaluation tendency. From the results of analysis, the participants were classified into 2 groups and “other”. The ratios of participants grouped in each cluster are shown in Fig. 4. In Fig. 4, each cluster is called as “Cluster-1” and “Cluster-2” in the descending order of rate of included participants.

![Cluster Analysis Graphs](image)

Figure 4: Ratio of participants grouped in each cluster from the results of cluster analysis

According to the result of cluster analysis, the obtained results in Fig. 2 are shown for each cluster in Fig 5.

<table>
<thead>
<tr>
<th></th>
<th>Low-speed range</th>
<th>Mid-speed range</th>
<th>High-speed range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster-1</td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td></td>
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<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>Cluster-2</td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
</tr>
</tbody>
</table>

Figure 5: Subjective evaluation scores of engine noise by general users after cluster analysis
As shown in Fig. 5, evaluation of dislike is increasing with ascending of the subjective scores of combustion noise by experts for the participants of Cluster-1 in all speed ranges. However, the participants of Cluster-2 did not show the same tendency to those of Cluster-1. The different evaluation tendency was observed between the participants grouped in Cluster-1 and Cluster-2.

### 3.2 Correlation with Subjective Evaluation of Previous Study

Correlation between the subjective scores of each cluster (see Sec. 3.1) and subjective evaluation scores of experts obtained in the previous study[2] is shown in Fig. 6. The vertical axis shows the evaluation scores of experts for combustion noise, and the horizontal axis shows the evaluation scores of general users for engine noise.

<table>
<thead>
<tr>
<th></th>
<th>Low-speed range</th>
<th>Mid-speed range</th>
<th>High-speed range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster-1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>By Experts</td>
<td>R² = 0.886***</td>
<td>By Experts</td>
<td>R² = 0.944***</td>
</tr>
<tr>
<td>By General Users</td>
<td>Good</td>
<td>By General Users</td>
<td>Good</td>
</tr>
<tr>
<td>Subjective score for combustion noise</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Subjective score for engine noise</td>
<td>-2</td>
<td>-1</td>
<td>0</td>
</tr>
</tbody>
</table>

| Cluster-2 |                 |                 |                 |
| By Experts | R² = 0.005 | By Experts | R² = 0.632*** | By Experts | R² = 0.329* |
| By General Users | Good | By General Users | Good | By General Users | Good |
| Subjective score for combustion noise | 2 | 1 | 0 | -1 | -2 |
| Subjective score for engine noise | -2 | -1 | 0 | 1 | 2 |

Figure 6: Correlation between the evaluation of engine noise by general users and those of combustion noise by experts

As shown in Fig. 6, the determination coefficient $R^2$ between Cluster-1 (the largest cluster for all speed ranges) and NVH development experts were high. Therefore, evaluation tendency of engine noise of the participants grouped in Cluster-1 is similar to that of combustion noise of the NVH development experts. However, $R^2$ between Cluster-2 and the NVH development experts showed scarcely correlation. The evaluation tendency of the participants grouped in Cluster-2 might be different from that of the participants grouped in Cluster-1 and the experts.

### 4. Discussion

#### 4.1 Correlation with Several Objective Indicators

In the introspection reports, the participants were required to answer the criteria on evaluation of dislike and sound characteristic of disliked engine noise (see Sec. 2.3). As a result, “strongly fluctuated”, “strongly unclear”, or “loud” were written as characteristics disliked engine noise.
To discuss the factor affecting the evaluation of dislike, we performed the multiple regression analyses using psychoacoustic metrics “fluctuation intensity” and “loudness” shown in Fig. 7. These metrics were originally constructed by Honda R&D Company[5, 6]. We set the subjective scores as objective variables, the sum of loudnesses from 1 to 18 Bark and the sum of fluctuation intensities from 3 to 18 Bark as explanatory variables. For the reference, the sum of fluctuation intensity from 3 to 18 Bark is equal to DCNI as the current sound quality index of combustion noise[2].

In the multiple regression analyses, the explanatory variables which had small p-value were removed beforehand. The results of multiple regression analyses are shown in Fig. 8.

Figure 7: Overview of the calculation flow of loudness and fluctuation intensity [5, 6]

N: Loudness (sone)  
F1: Fluctuation intensity (mon)  
z: Critical band (Bark)

<table>
<thead>
<tr>
<th></th>
<th>Low-speed range (1500 – 2500 rpm)</th>
<th>Mid-speed range (3500 – 4500 rpm)</th>
<th>High-speed range (5500 – 6500 rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Subjective score</td>
<td>Subjective score</td>
<td>Subjective score</td>
</tr>
<tr>
<td>Cluster-1</td>
<td>$R^2 = 0.884^{***}$</td>
<td>$R^2 = 0.863^{***}$</td>
<td>$R^2 = 0.896^{***}$</td>
</tr>
<tr>
<td></td>
<td>$0.072^{**}$</td>
<td>$0.111^{***}$</td>
<td>$0.080^{***}$</td>
</tr>
<tr>
<td>Cluster-2</td>
<td>$R^2 = 0.897^{***}$</td>
<td>$R^2 = 0.883^{***}$</td>
<td>$R^2 = 0.948^{***}$</td>
</tr>
<tr>
<td></td>
<td>$0.121^{***}$</td>
<td>$0.083^{***}$</td>
<td>$0.069^{***}$</td>
</tr>
</tbody>
</table>

Figure 8: Multiple regression analyses for the subjective scores of engine noise using loudness and fluctuation intensity
The multiple regression models shown in blue are strongly affected by fluctuation intensity. The multiple regression model shown in red have strongly affected by loudness. The multiple regression models shown in violet have affected by both of fluctuation intensity and loudness.

Consequently, the participants of Cluster-1 in each speed range mainly evaluated the engine noise according to the degree of fluctuation for all speed ranges. The participants of Cluster-2 in low-speed range evaluated the stimuli based on their loudness, and in mid-speed and high-speed range, evaluated based on both of their degree of fluctuation and loudness.

4.2 Evaluation Characteristics

From the results shown in Fig. 8, evaluation tendency of each cluster for each speed range are shown in Fig. 9. As shown in Fig. 9, in any speed ranges, to decrease DCNI is valid for more than 50% of them for all speed ranges. Therefore, the validity the effectiveness of reducing DCNI for general users was discussed in this paper. However, the participants of Cluster-2 in low-speed range are not valid for reducing dislike by decreasing DCNI, reducing loudness of combustion noise has to consider for them to improve the dislike feeling.

![Evaluation characteristics of each cluster](image-url)

5. Conclusion

The subjective evaluation experiment was conducted for general users, the technical term “combustion noise” was replaced to the general term “engine noise”. The results of the experiment were varied widely for all speed range compared with those of experts for combustion noise.

We performed cluster analyses for the results, it was found that the participants were able to group 2 clusters in each speed range.

Using the sum of loudness from 1 to 18 Bark and the sum of fluctuation intensity from 3 to 18 Bark as explanatory variables, the multiple regression analyses were conducted to the averages of subjective scores of the clusters. As a result, the participants were able to be grouped into 3 groups, the group who considers fluctuation intensity is important, the group who considers loudness is important, and the group who considers the both of fluctuation intensity and loudness are important.

In any speed ranges, the participants of the most populated cluster consider that fluctuation intensity is important for the evaluations. For these clusters, reducing the fluctuation of combustion noise by DCNI is valid.

For the participants of the other clusters except for above clusters, reducing loudness of combustion noise is important.

From these results, not only DCNI but loudness is needed to include in the evaluation index for improving combustion noise effectively.
6. Future Works

In this paper, only young university students were participated in the experiment. To discuss along the actual population ratio of general users of vehicle, more participants with various generation are needed to participate.

The experimental results of this paper were different from those of experts for combustion noise, however, we cannot conclude the factor of the difference, the participants or replacement of the term “combustion noise” with “engine noise”. It will be proved from the experiment evaluating “engine noise” by experts.

7. Acknowledgements

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REFERENCES


