MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

Study of Sound design using Passive Noise Control in automobile

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ABSTRACT

Recent year, Active Noise Control(ANC) and Passive Noise Control(PNC) have attracted attention as noise reduction in automobiles. It is thought that noise control is able to control not only sound pressure but also auditory impression. In recent years, as the quality of automobiles is developing day by day, the driving sound of automobiles has become one of the important factors that affect an auditory impression. In other words, the engine sound control has been shifting from noise control to sound design. In this study, we investigated how the impression of engine sound changes by sound absorbers. We measured the engine sound in the automobile with or without absorbers. After that, we analyse these sounds using the SD method and factor analysis to find a subjective impression. As a result, we clarified the subjective indicator (adjective pair) that affected the auditory impression. Moreover, we clarified that it is possible to add specific sound impression with some sound absorbers.

Keywords: sound absorbers, sound design, SD method, MUSHRA
I-INCE Classification of Subject Number: 35

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1. INTRODUCTION

In recent years, passive noise control (PNC) technology has been employed as a noise reduction method in automobiles [1]. Generally, noise reduction is performed with sound absorbers or sound insulations. Improvement of noise suppression in automobiles has been actively investigated in numerous previous studies. However, there is the possibility that a reduction in noise may cause drivers to perceive a greater level of road and wind noise. Furthermore, automobiles are often used recreationally and described as “fun to drive" and "fun to ride." It is certain that some people drive for pleasure and these drivers may experience less enjoyment if the engine sound is reduced by PNC. In addition, engine sound has been shifting from noise reduction to sound design in the production of high-end automobiles [2][3]. According to our previous study, the differences in each participant’s preference affects their impression of engine sound [4][5]. In this study, we investigated the auditory impression of automobiles with sound absorbers. Specifically, we aimed to identify adjective pairs as the subjective indicators that affect auditory impression.

2. SOUND EXPERIMENT

2.1 Driving Conditions

We recorded the engine sound inside an automobile driven on a chassis dynamo. A dummy head (G.R.A.S/45BA) was installed in the front passenger seat. Recordings were performed at a sampling frequency of 65,536 Hz and a quantization bit number of 24 bits using a digital recorder (Bruel & Kjar / LAN-XI 3050-060). We recorded the engine sound with and without sound absorbers. Table 1 shows the five driving conditions that were investigated. The recordings were made under the following three conditions: 1) with sound absorbers 2) without sound absorbers in the engine room, and 3) without sound absorbers in the engine room and instrument panel. In total, we recorded the sound in 15 situations related to the driving and sound absorber conditions.

Table 1 - Driving conditions

	Accelerated driving	Steady driving
Second gear	Full throttle (800–5000 rpm)	
Third gear	Full throttle (800–5000 rpm)	60 km/h
Dynamic range	Full throttle (120 km/h)	60 km/h, 100 km/h

2.2 Characteristics of Sound Absorbers

We conducted frequency analysis for the steady driving sound and spectrogram analysis for the accelerated driving sound. Fig. 1 shows the frequency analysis results for the steady driving sound in the dynamic range. Fig. 2 shows the results of the spectrogram analysis for accelerated driving sound in the dynamic range. The broken blue line and solid red line represent the frequency characteristics with and without sound absorbers, respectively.

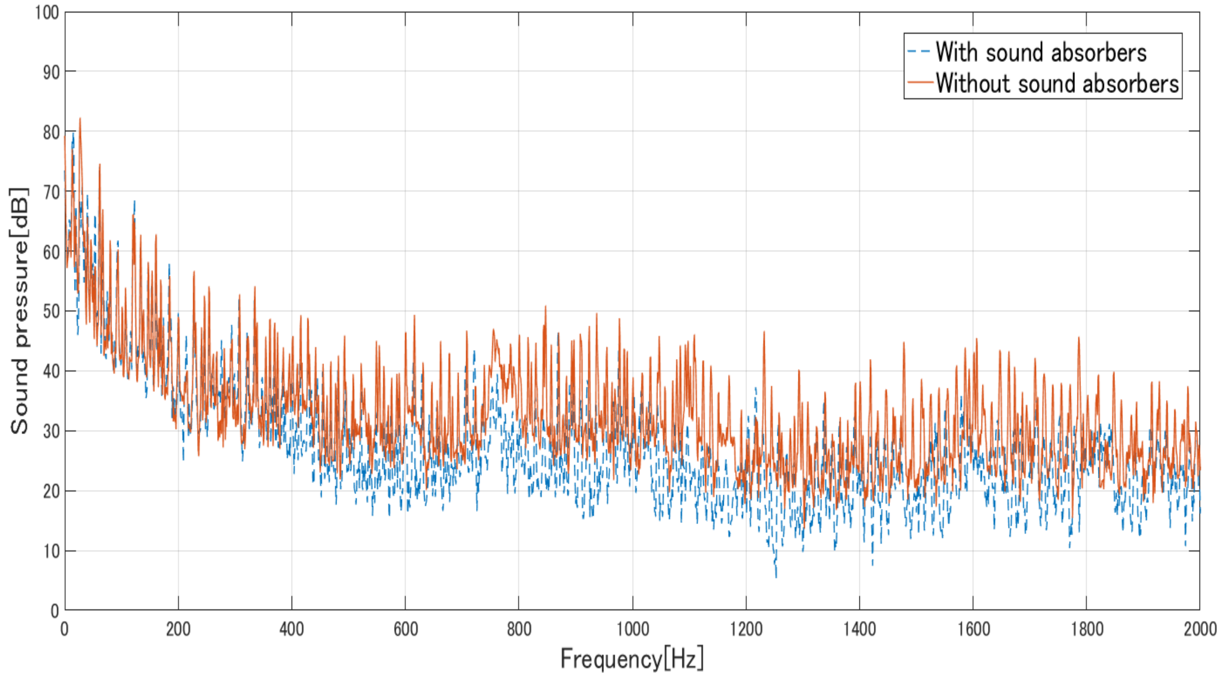
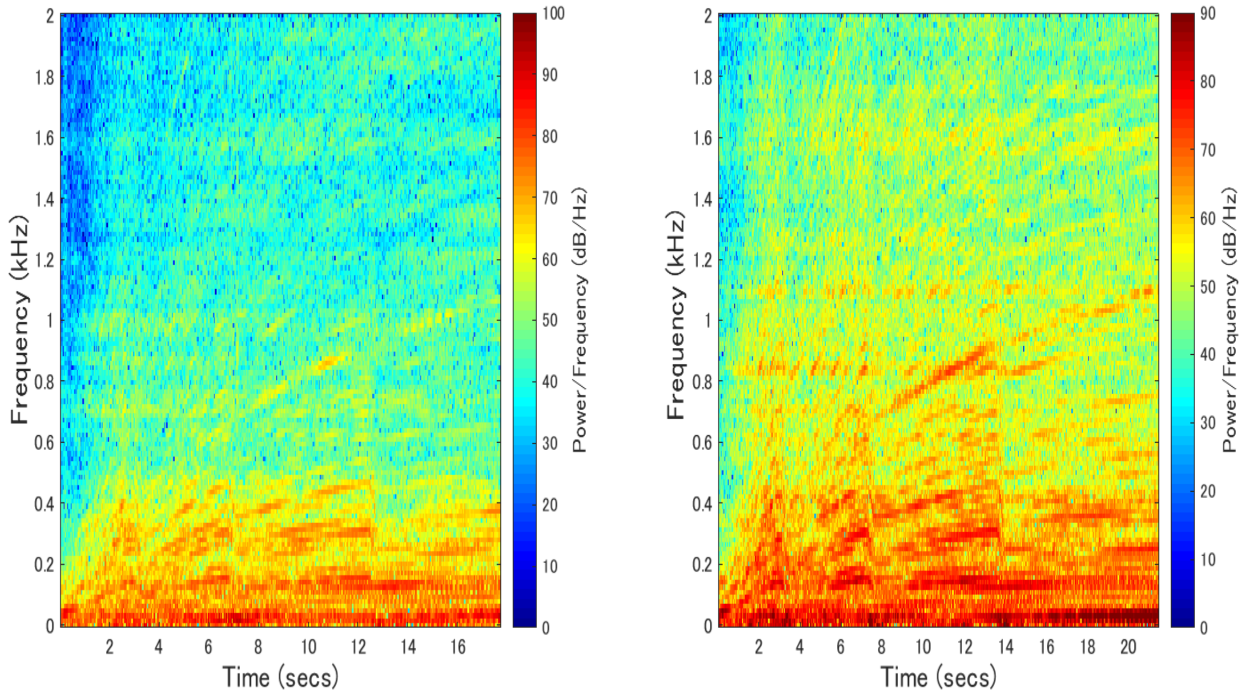


Fig. 1 - Frequency analysis of steady driving (dynamic range 100 km/h); broken blue and solid red lines represent the frequency characteristics with and without sound absorbers, respectively.



(a) With sound absorbers *(b) Without sound absorbers*

Fig. 2 - Spectrogram analysis of accelerated driving (dynamic range 120km/h)

The results shown in Figs. 1 and 2 confirm that sound absorbers reduce the sound pressure label over approximately 400 Hz. A maximum reduction of 12 dB was confirmed this identifies a band where sound absorbers are effective in reducing engine sound.

3. ADJECTIVE SELECTION EXPERIMENT

To identify auditory impression through factor analysis and the SD method, we conducted an adjective selection experiment [6]. We selected adjectives related to engine sound using the following method.

3.1 Adjective Selection through Brainstorming

We brainstormed on “high-quality- sporty feeling,” and selected adjective pairs from six individuals, including workers in the automobile industry. We avoided ambiguous interpretations and summarized similar adjective pairs. Through this work, 45 adjectives were selected as shown in Table 2.

Table 2 - Adjectives selected through brainstorming

Cool, Powerful, Closed, Fluffy, Excited, Smooth, Impressive, Japanese Style, Listenable, Sporty, Fierce, Bright, Consecutive, Cleary, Discreet, Heavy, Comfortable, Beautiful, Bustling, Deep, Expensive, Acceleration, Soft, Radiant, Restful, Modest, Thrilled, Echoic, Pleasant, Warm, Delicate, Sharp, Expansive, Clogged, Noisy, High, Refreshing, Hot, Round, Obvious, Glamorous, Familiar, Speedy, Dry, Simple

3.2 Adjective Selection using the SD Method

In the auditory experiments, it was necessary to exclude the adjectives that are unrelated to the “high-quality sporty feeling” from the adjective list in Table 2. Therefore, we selected the highly relevant ones from the preliminary experiment. Specifically, we conducted an auditory impression experiment using the SD method. The experiment involved 23 participants (aged 20 – 24). In this study, the stimulus sound was an accelerated driving (third gear) sound, with and without sound absorbers in the engine room and instrument panel, as described in section 2. Subsequently, we conducted factor analysis on the data from the auditory impression experiment and selected adjective pairs. Table 3 shows the result of the selection of the adjective pairs through factor analysis. As a result, we obtained 30 adjectives as an evaluation index.

Table 3 - Adjectives related to engine sound

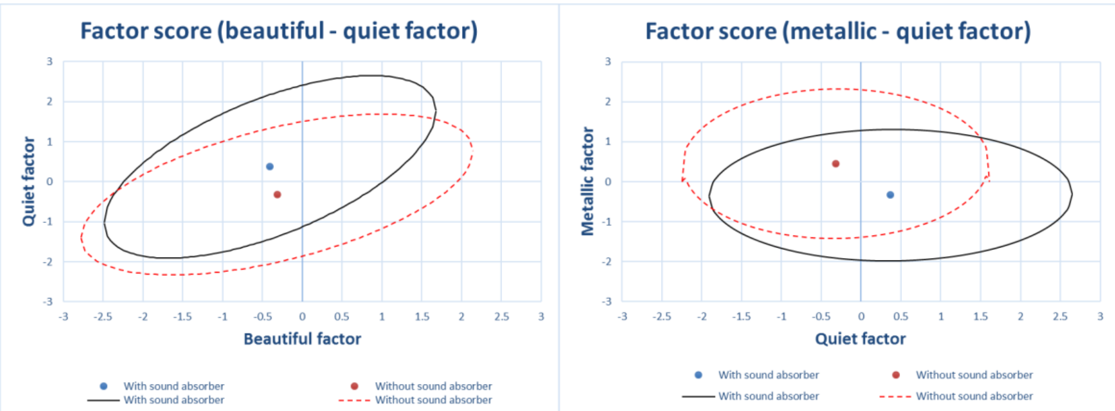
Cool, Powerful, Fluffy, Excited, Listenable, Sporty, Fierce, Bright, Consecutive, Cleary, Discreet, Heavy, Comfortable, Bustling, Expensive, Soft, Radiant, Modest, Excited, Echoic, Pleasant, Warm, Delicate, Sharp, Expansive, Noisy, High, Refreshing, Round, Glamorous

3.3 Auditory Impression Experiment

Using the above results, we conducted an auditory impression experiment using the evaluation index obtained. The SD method was employed for the evaluation, which involved 32 participants aged 20 – 60, who worked in the automobile industry.
The following types of sound sources were prepared as the stimulus sounds:
1) Engine sound with sound absorbers (accelerated driving in third gear).
2) Engine sound without sound absorbers in the engine room and the instrument panel (accelerated driving in the third gear).
3) Engine sound with sound absorbers (steady driving in third gear).
4) Engine sound without sound absorbers in the engine room and the instrument panel part (steady driving in third gear).
The stimulus sound was presented to the participants using open headphones (SENNHEISER/HD 598) while the stimuli were randomly presented.

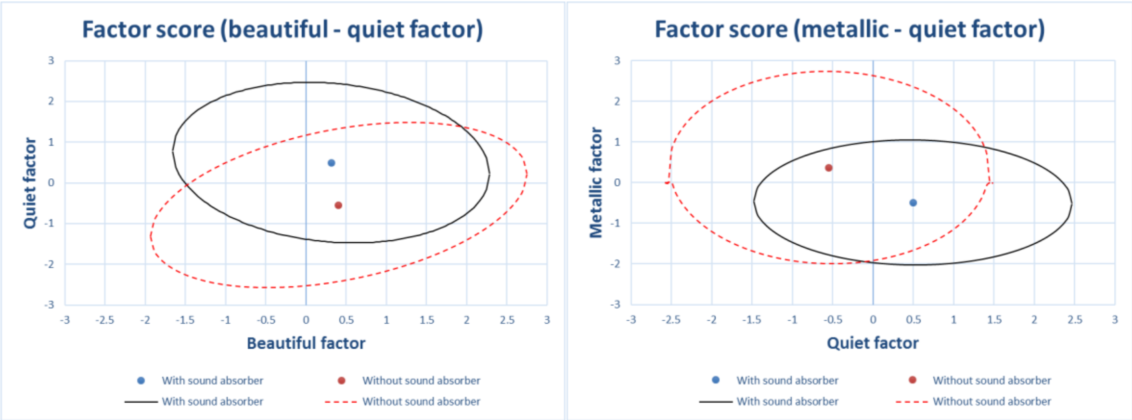
3.4 Factor Analysis Results

Factor analysis was performed on the data obtained from the auditory experiment. We used the maximum likelihood method for factor extraction and promax rotation as the rotation method for each. The factor analysis results indicated that the automobile engine sound comprises three factors, namely beautiful factor, quiet factor, and metallic factor. The factor score results are shown in Figs. 3 and 4. As seen in these figures, the quiet factor increases in the analysis with sound absorbers while the beautiful and metallic factors both increase in the case without sound absorbers. These results shows a trade-off between a quiet and sporty feeling for automobile engine sounds. Hence, to realize the "high quality sporty" sound quality, it is important to achieve a balance on these factors.



(a) Factor score (beautiful – quiet factor) *(b) Factor score (metallic – quiet factor)*

Fig. 3 - Factor score for steady driving



(a) Factor score (beautiful – quiet factor) *(b) Factor score (metallic – quiet factor)*

Fig. 4 - Factor score for accelerated driving

4. AUDITORY EXPERIMENT OF PROCESSED SOUND SOURCE

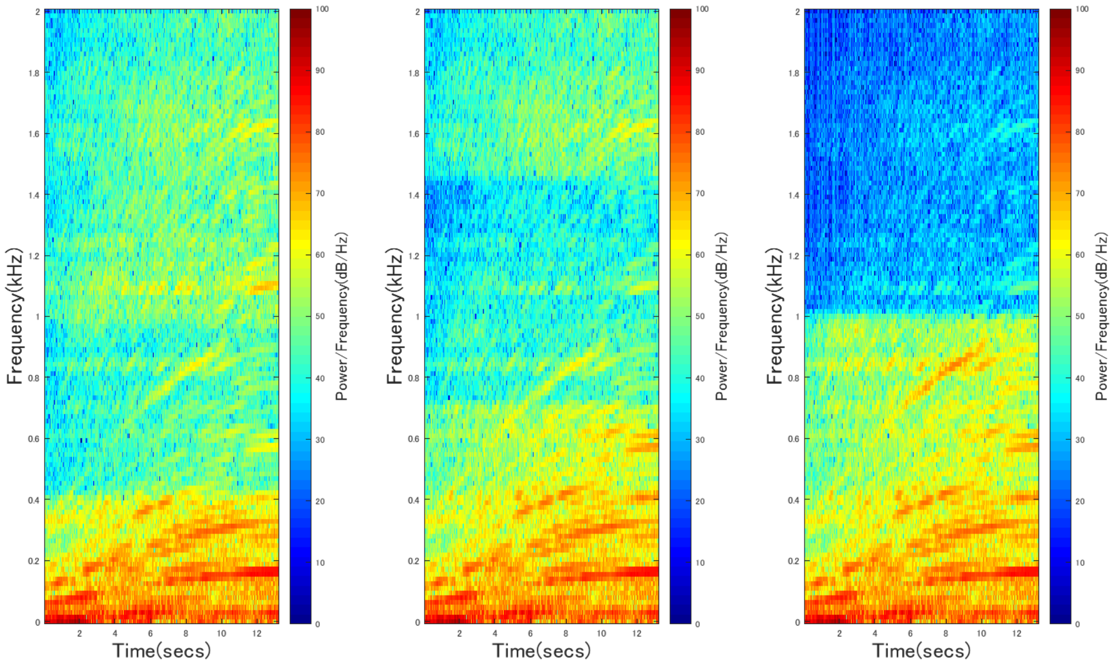
We assessed the effect of band attention on the engine sound on auditory impression, in order to identify the differences owing to the presence or absence of sound absorbers. Specifically, we investigated the change in impression with changes in the reduction range.

4.1 Stimuli

We employed a band-stop filter and a high-pass filter to process the engine sounds as stimuli. The characteristic of the combined band-stop and high-pass filter were those of a fifty-order finite impulse response filter. Frequencies below or above the cut-off frequencies were attenuated by 10 dB for the filter combination used. Signals were attenuated from ranges 400 to 1,000 Hz or from 700 to 1,500 Hz by the band-stop filter, or over 1,000 Hz were the high-pass filter. The frequency characteristics of each processed engine sound are shown in Fig. 5.

4.2 Auditory Impression Experiment

In this study, we conducted an auditory experiment to identify the sound associated with a "high - quality sporty feeling." We conducted an auditory impression experiment using Scheffe’s method of paired comparisons [7]. Scheffe’s method was employed for the evaluation with 41 participants (aged 20 - 60; 32 males, 9 females) who worked in the automobile industry. Five types of stimulus sound were used: a) with sound absorbers, b) attenuated from 400 to 1,000 Hz, c) attenuated from 700 to 1,500 Hz, d) attenuated over 1000Hz, and e) without sound absorbers. The participants evaluated different sounds to determine which ones they most strongly associated with a high-quality sporty feeling. The Scheffe’s method results are shown in Fig. 6.



1) 400 ~ 1000Hz *2) 700 ~ 1500Hz* *3) over 1000Hz*

Fig. 5 – Processed engine sound

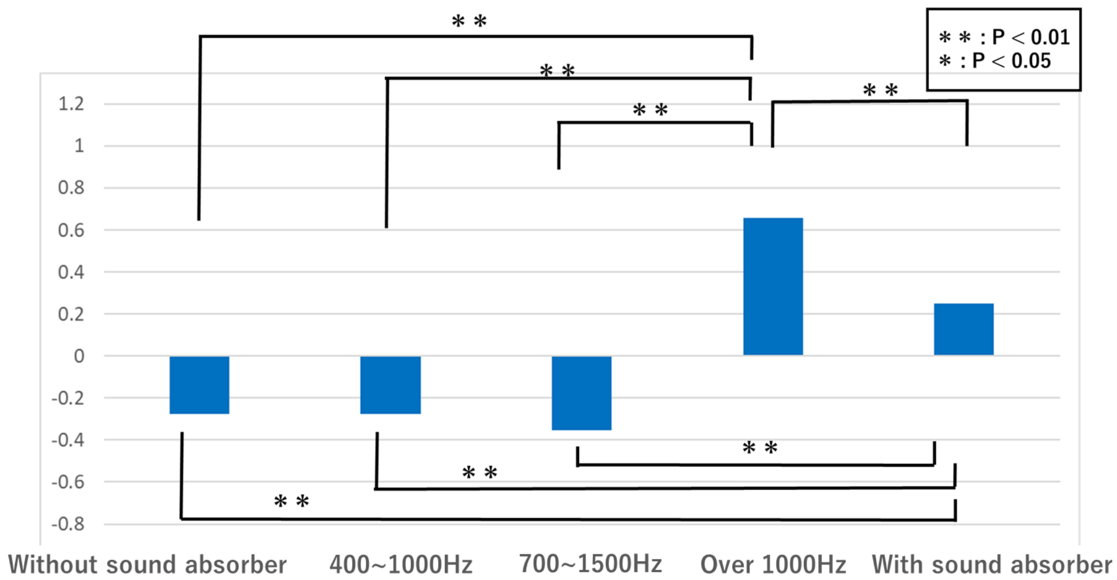


Fig. 6 - Scheffe's method results

The results confirm that the high-quality sporty sound was created by the attenuation of engine sounds at frequencies over 1,000 Hz. It can also be seen that there are significant differences between the stimuli. From this result, each participant can identify "High quality sporty feeling".

5. Auditory impression experiment by MUSHRA method

We examined the correspondence between the band of 1000 Hz over and a high-quality sporty feeling through this experiment. We used MUSHRA(Multiple Stimuli with Reference and Anchor, ITU-R BS.1534-3) method to examine "high-quality sporty" in the band of over 1000 Hz.

5.1 Stimuli

We used the same filter as in Chapter 4 for increasing and decreasing engine sound. Frequencies below or above the cut-off frequencies were attenuated by 10 dB for the filter combination used. Signals were attenuated by 10dB over 1,000 Hz, 2,000Hz, 3,000Hz, 4,000Hz and 5,000Hz by the high-pass filter. We amplified by 10dB for the first and second order components. The frequency characteristics of each processed engine sound are shown in Figs. 8 and 9.

5.2 Auditory Impression Experiment

We adopted the MUSHRA method to characterize "high - quality sporty feeling" between the stimuli. With this method, it is possible to characterize the difference between the stimuli by the mean and variance. We examined the relationship between "high - quality sporty feeling" and frequency bands over 1000 Hz. The MUSHRA method was employed for the evaluation with 36 participants (aged 20 - 50; 28 males, 8 females) who worked in the automobile industry. Seven types of stimulus sound were used: a) with sound absorbers, b) attenuated over 1,000Hz, c) attenuated over 2,000Hz, d) attenuated over 3,000Hz, e) attenuated over 4,000Hz, f) attenuated over 5,000Hz, and g) with amplitude component amplification. The participants evaluated different sounds to determine which ones they most strongly associated with a high-quality sporty feeling. The MUSHRA method results are shown Fig. 10.

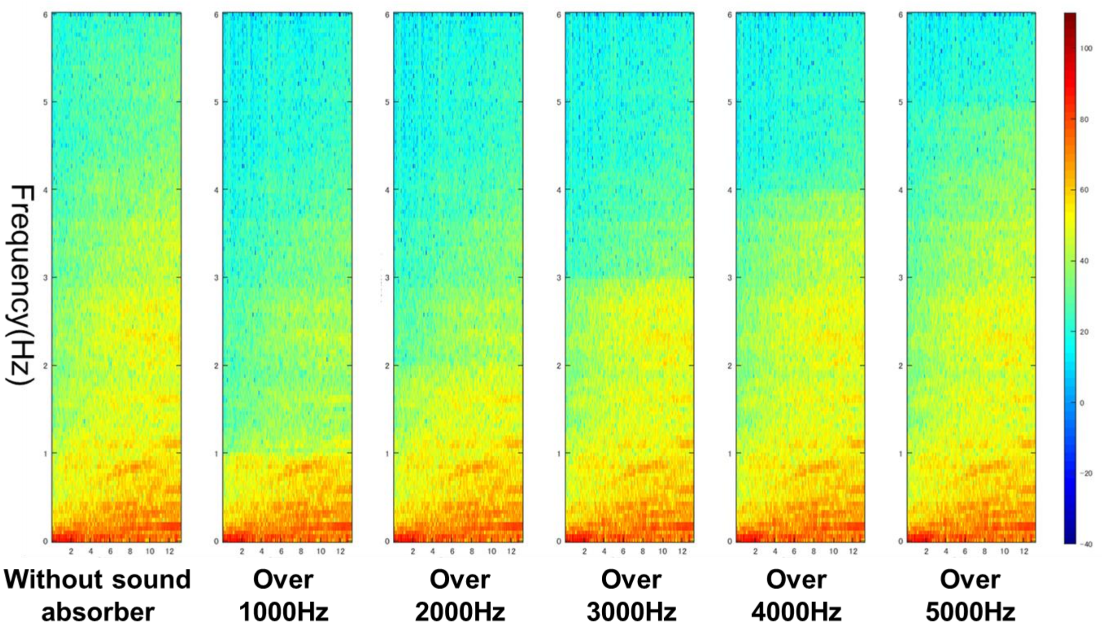
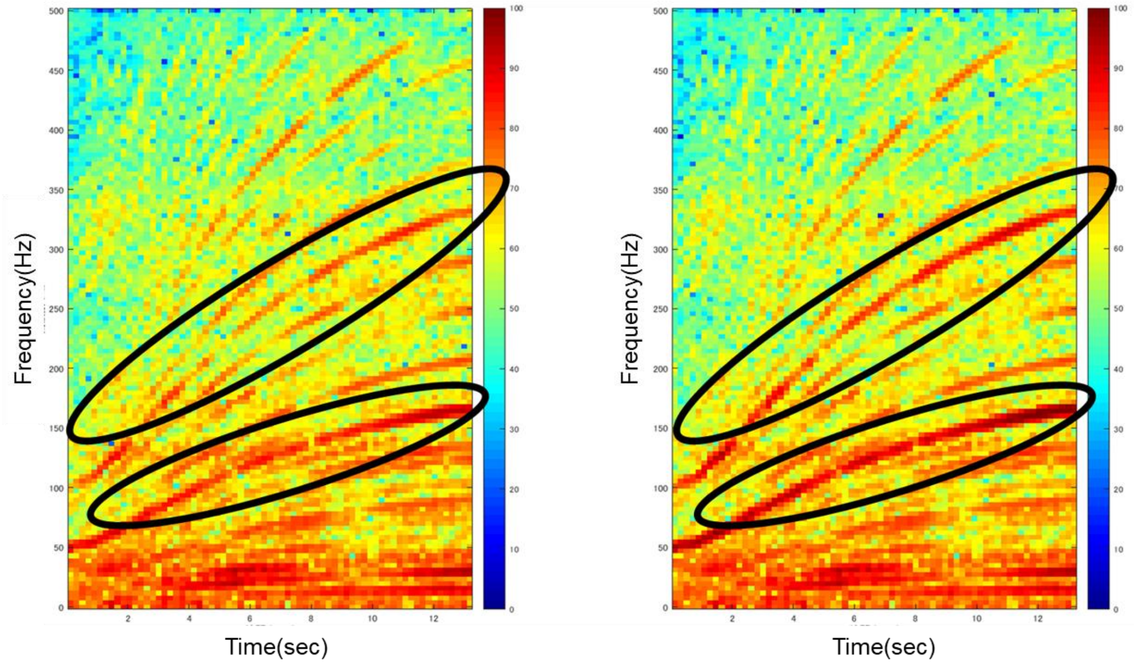


Fig. 8 – Processed engine sound



a) With sound absorber *b) Amplitude component amplification*

Fig. 9 – First-order and second-order component amplification

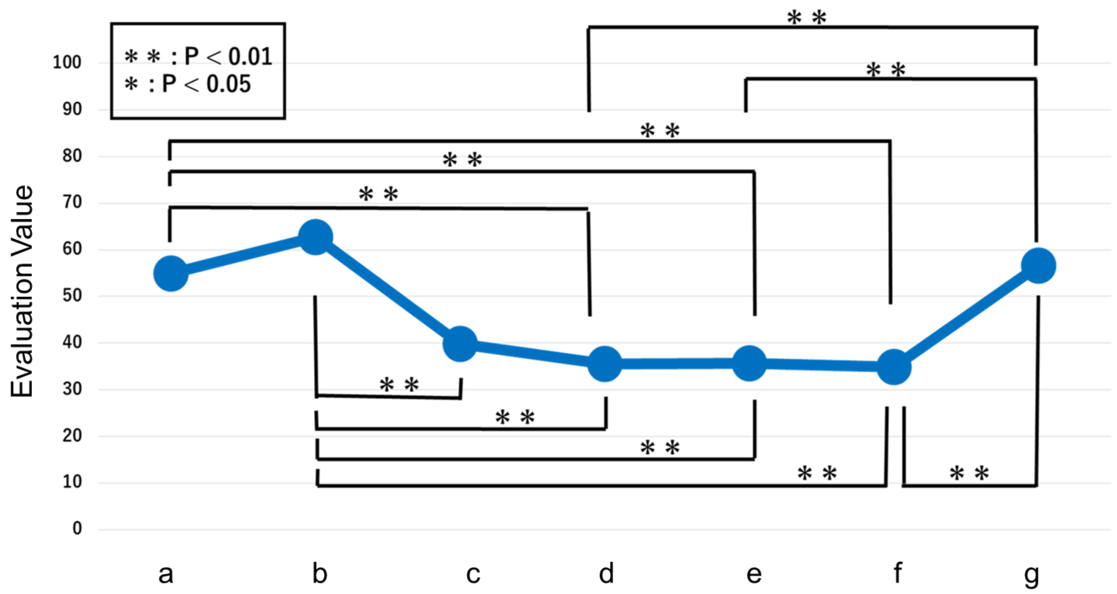


Fig. 10 – MUSHRA method results

From the results, we identify the frequency band which is most characterized by a "high - quality sporty feeling". By reducing frequencies over 1,000Hz, the impression of a "high - quality sporty feeling" increased. From the results of Section 4 and 5, it seems that it might be possible to influence driver perception by selective sound absorption. Additionally, we suggest the possibility of oparating the impression by sound absorption control.

6. CONCLUSION

In this study, we investigated the effects of sound absorbers on engine sound in automobiles using a subjective evaluation. We used the SD method, factor analysis, Scheffe's method and MUSHRA method to characterize the impression. The results demonstrate that sound absorbers affected not only quietness, but also the sense of excitement and sportiness perceived by the driver. In future work, we will investigate sound quality control through the use of a sound absorber for each frequency band. We believe that it is possible to add an intended sense or feeling through sound absorber control of particular frequency bands. Finally, we have laid a foundation for the future examination of the correspondence between sound absorption control and perception.

7. REFERENCES

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