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Design of optimal car interior sound improving driving feeling

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ABSTRACT

The virtual driving sound has been used as a tool improving the driving feeling of passenger car. The purpose of this study is to suggest the strategy generating virtual driving sound that is closely connected with the driving condition. To this end, previous studies ascertained that powerful feeling of car interior sound was related to the roughness during the acceleration and that dynamic feeling and pleasant feeling of car interior sound were negative correlation. In this study, the acoustic factor affecting dynamic feeling was extracted based on the subjective listening evaluation. And by using the acoustic factor, it was identified to improve the driving feeling when a virtual sound should be generated and what order components should be supplemented. It is expected that the method can improve driving feeling related to not only dynamic feeling but also pleasant feeling.

Keywords: Sound Quality, Driving Feeling, Driving Sound, Dynamic Feeling

1. INTRODUCTION

The studies to improve the driving feeling of the car have been on-going as the expectation on the perceived quality have been surged. For this issue, there is a way to control the actual engine sound by using the intake and exhaust system, but recently, the virtual driving sound is produced in use of the audio system by the reasons of physical restrictions such as the structure of engine and car body and regulating on the external sound. In order to improve the driving feeling of the car with virtual driving sound, the strategy of designing the driving sound tuned to the driving conditions is required.

When the precedent studies for designing the driving sound were looked into, Frank et al. (1) described that the roughness was related to a powerful sound for the sporty car, and the roughness was increased by amplitude modulation when the neighboring half-order of the main order on the engine was amplified. Wang et al. (2) described that the roughness improve the powerful feeling of the sporty car, but it induce the annoying in the usual car. Cha (3) and Kim (4) classified the dynamic feeling into a powerful feeling and a speedy feeling based on the subjective listening evaluation and described the reduced pleasant feeling at the improved the dynamic feeling. This study is to suggest the virtual driving sound design strategy to improve the driving feeling that improves dynamic feeling during the acceleration and keeps the pleasant feeling during the constant or deceleration.

To this end, Section 2 measured the driving sound for the cars with different engine performance in various driving conditions, Section 3 performed the subjective listening evaluation on the measured driving sounds for the driving feeling evaluation. Section 4 derived the acoustic factors to analyze the subjective listening evaluation as objective, and Section 5 proposed the strategy generating virtual driving sound to improve the driving feeling.

2. Measurement of driving sound

As shown in Table 1, the driving sound was measured for Car A and Car B differed in engine performance (Power & Torque) through the microphone installed at the driver's ear position.

The cars were driven in acceleration after initial cruising speed, and the specific driving conditions were constructed in 1-4 steps as shown in Table 2. In this paper, the driving conditions were described in sequence of initial cruising speed and acceleration conditions. For example, as shown in Figure 1,

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it was expressed in 80km/h MTI in case of 80km/h initial cruising (constant) speed and Middle Tip In (MTI) acceleration.

Table 1 – Comparison of the engine performances

Engine performance / Cars sample	Maximum power	Maximum torque
Car A	332 kW @ 5,500 rpm	651 N·m @ 1,800 ~ 4,500 rpm
Car B	272 kW @ 6,000 rpm	510 N·m @ 1,300 ~ 4,500 rpm

Table 2 – Driving conditions for recording

Driving condition / Step	Initial cruising speed	Accelerating condition
Step1	80km/h	MTI
Step2	100km/h	MTI
Step3	80km/h	WOT
Step4	100km/h	WOT

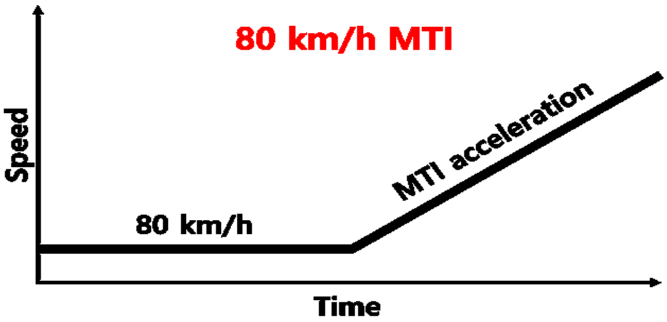


Figure 1 – Method of the driving according to speed vs. time

3. Subjective listening evaluation for driving feeling

3.1 Construction of subjective listening evaluation

As shown in Figure 2, the test sound was made for the measured driving sound in Chapter 2 by editing in acceleration interval after keeping the initial cruising speed for 1 second. Because these sounds were more than 10 second and are non-stationary sound, the listening evaluation program was made as shown in Figure 3(a) and used to evaluate on each section. Magnitude Estimation Method (MEM) was applied to the listening test, and the levels of dynamic feeling were evaluated with the criteria of Figure 3(b). The jury was composed of 30 people in 20-30s having normal hearing ability.

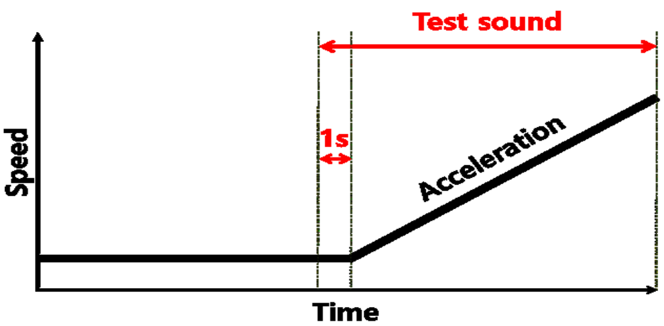


Figure 2 – Change of test sound in time domain

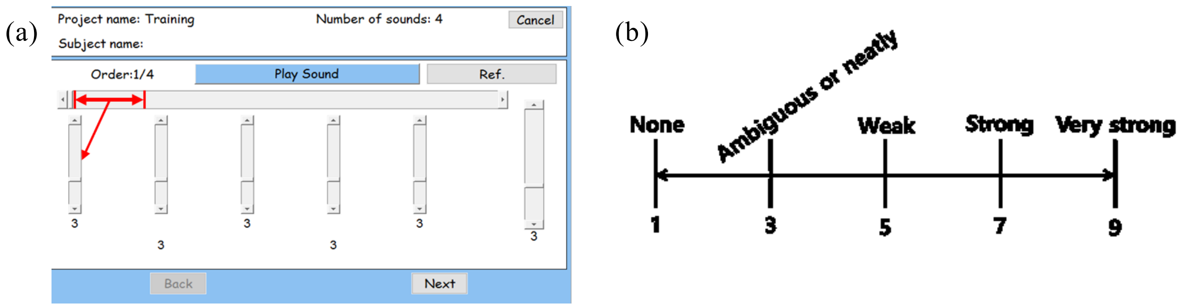


Figure 3 – (a) Listening evaluation program for acceleration sound,

(b) Rating guide for dynamic feeling

3.2 Results of dynamic feeling evaluation

As shown in Figure 4, Car A with more good in engine performance was evaluated higher than Car B in the overall acceleration section. The result can be analyzed for the reflection of engine performance to the dynamic feeling.

Next, the relation between the driving characteristics and dynamic feeling was analyzed as follows. Firstly, the dynamic feeling had more than 3.5 points for Car A and less than 2.8 points for Car B at the initial acceleration section, and later, tended to increase for both Car A and B at the acceleration. In the other words, the improvement on the dynamic feeling at the initial acceleration section will be effective to improve the overall dynamic feeling during accelerated driving.

Secondly, the driving conditions of the Car A with high performance engine were compared in the acceleration section as follows. The dynamic feeling was increased comparatively in linear form in Wide Open Throttle (WOT) acceleration, but increased in log form in MTI acceleration. In the other words, it is considered that the difference in acceleration amount (or supplied power) made influence on the dynamic feeling at the acceleration section.

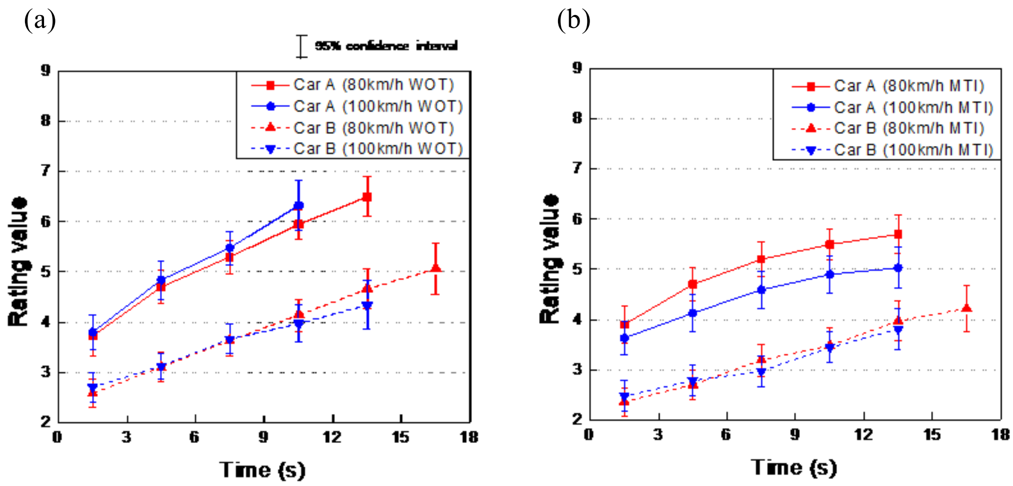


Figure 4 – Result of Subjective listening evaluation

(a) WOT acceleration conditions, (b) MTI acceleration conditions

4. Method to analyze dynamic feeling objectively

For objective analysis on dynamic feeling, Section 4.1 analyzed driving sound by means of Short Time Fourier Transform (STFT) and Section 4.2 suggested the TNR_{order} for acoustic factor to reflect the features in engine sound. And Section 4.3 analyzed the influential factors to the dynamic feeling objectively with TNR_{order}.

4.1 STFT Analysis

Figure 5 showed the calculated STFT of each car (Car A & Car B) for 80km/h WOT. In case of Car

A, the 1st firing order of the engine was mainly occurred in the initial acceleration section and the 2nd firing order was mainly occurred at the section after 8s. For Car B, however, the firing order components were not dominant or clear through the acceleration section.

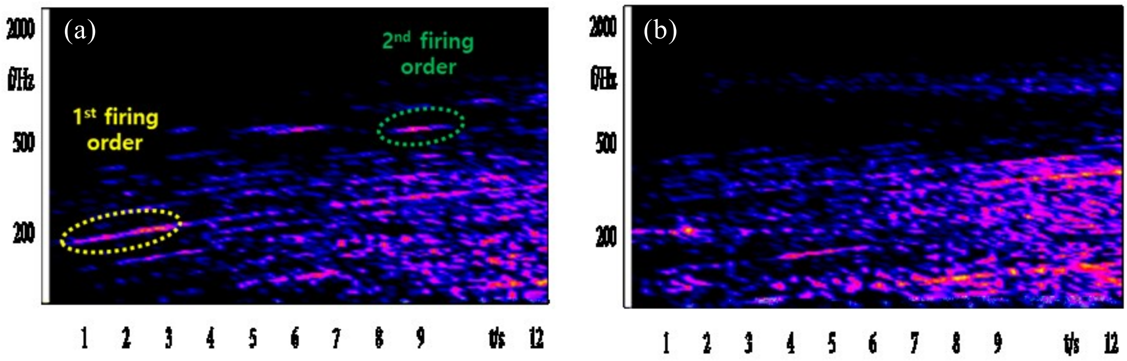


Figure 5 – Results of STFT analysis for 80km/h WOT (a) Car A, (b) Car B

4.2 $\mathrm{TNR}_{\mathrm{order}}$

Tone to Noise Ratio (TNR) (6) presented the log scale for the calculated ratio of tone power to noise power as shown in Eq. 1 to reflect the features of tonal sound. The critical-bandwidth, 1Bark for ISO 532-1 (7) was adopted for the frequency range of the noise power.

But, differently with TNR, $\mathrm{TNR}_{\mathrm{order}}$ presented the log scale for the calculated ratio of tone power to noise power of target engine order. The Equivalent Rectangular Bandwidth (ERB), 1Cam for ISO 532-2 (8) was adopted for the frequency range to obtain the noise power. The reason was to minimize the interference of neighboring engine order for the target engine order on the frequency range corresponding to noise power because 1Cam is narrower than 1Bark on the frequency below 500Hz where engine sound occurred mainly. Figure 6 showed the frequency range of 1Cam for obtain the noise power of the 1st and 2nd firing order. $\mathrm{TNR}_{\mathrm{order}}$ was calculated through Eq. 1 after obtaining tone power and noise power.

$$\mathrm{TNR} = 10log_{10}\frac{Tone\ \ power}{Noise\ \ power} \tag{1}$$

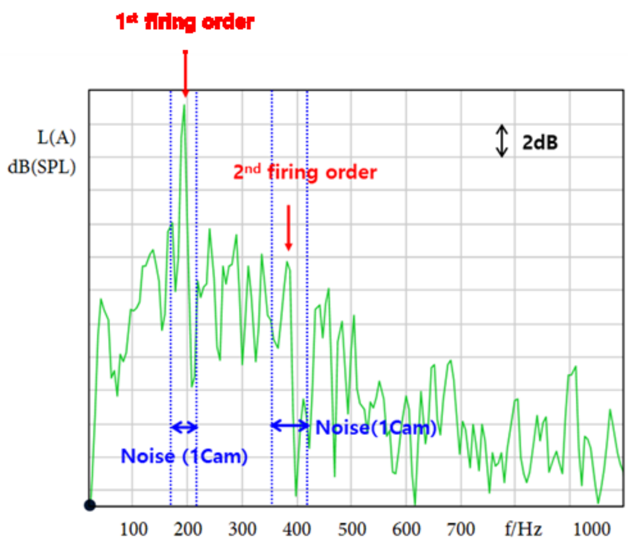


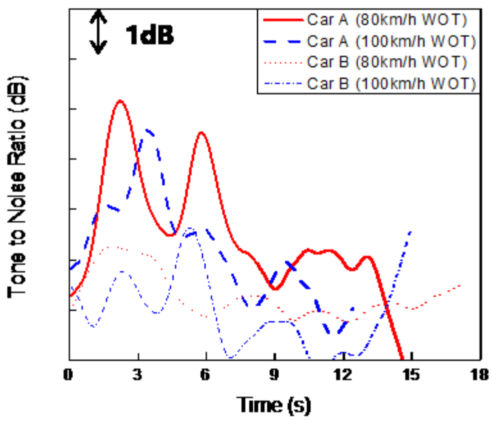
Figure 6 – Order components and frequency ranges of noise component for $\mathrm{TNR}_{\mathrm{order}}$

4.3 The relation between $\mathrm{TNR}_{\mathrm{order}}$ and dynamic feeling

The influential factors on the dynamic feeling was analyzed objectively with $\mathrm{TNR}_{\mathrm{order}}$. First, Figure 7(a) shows the calculated $\mathrm{TNR}_{\mathrm{order}}$ of the 1st firing order when the acceleration conditions of Car A and Car B were WOT. It shows TNR_{order} was more than twice higher in Car A than Car B in the initial acceleration section. This result can be regarded as TNR_{order} difference of the 1st firing order by the differences of engine and the performance of NVH control of Car A and B. In other words, the sound pressure level (SPL) of the engine sound is reinforced when the 1st firing order was emphasized at the initial acceleration section, and such phenomenon was concluded as the differences of dynamic feelings for each car (Car A & Car B) in the initial acceleration section.

Next, Figure 7(b) shows the calculated TNR_{order} of the 2nd firing order on all driving conditions of Car A. It shows TNR_{order} of the 2nd firing order was decreased after the certain timing during acceleration in MTI condition, but TNR_{order} of the 2nd firing order was high after the certain timing during acceleration (WOT 80km/h: near to 11.5s, WOT 100km/h: near to 9.5s). This result can be regarded as TNR_{order} difference of the 2nd firing order by difference of acceleration amount for WOT acceleration and MTI acceleration in high speed driving and the structural resonance of the Car A in the frequency range corresponding to the 2nd firing order at certain timing during WOT acceleration. In other words, the tone color was changed when the high order was emphasized at the certain timing during acceleration, and such phenomenon was also concluded as the increased dynamic feeling on WOT acceleration duration.

(a)



(b)

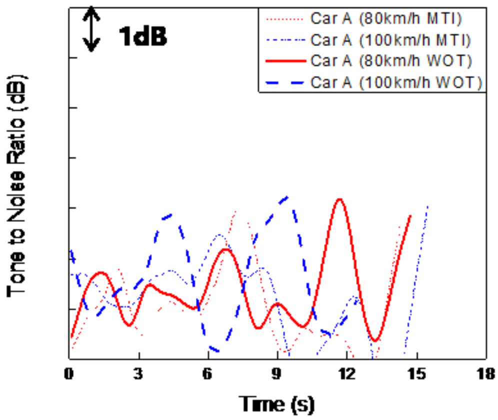


Figure 7 – Results of TNR_{order} vs. Time

(a) TNR_{order} for 1st firing order, (b) TNR_{order} for 2nd firing order of Car A

5. DISCUSSION

In section 4.3, the reinforcement of SPL for the engine sound by using the 1st firing order at the initial acceleration section and the change of tone color for the engine sound by using the high order at certain section during acceleration were known to be effective for the dynamic feeling enhancement. In other words, the reinforcement of the appropriate order component of engine sound and its generating timing were more effective to improve the dynamic feeling than the overall level was simply increased.

In addition, Kim (4) classified the dynamic feeling into the speedy feeling and the powerful feeling, and Cha et al. (3) described that the reinforcement of the high engine order was effective to improve for the speedy feeling. And, Frank et al. (1) described that the reinforcement of the half engine order was effective to improve for the powerful feeling. It is considered that the dynamic feeling can be improved by strengthening the speedy feeling as supplementing higher order and/or the powerful feeling as doing the roughness while the SPL of the car interior is kept when the virtual driving sound is generated

Based on the descriptions in the above, the strategy for creating the virtual driving sound to improve the driving feeling was proposed in Figure 8. In the constant speed section corresponding to '$T_0 \sim T_1$', the virtual driving sound is not generated, thereby keeping the pleasant feeling. In the acceleration section corresponding to '$T_1 \sim T_2$', because the acceleration amount is kept, the dynamic feeling is improved by generating a virtual driving sound to increase TNR_{order} of the 1st firing order. In the acceleration section corresponding to '$T_2 \sim T_3$', because the SPL on the car interior is high, the dynamic feeling is improved through the speedy feeling is improved by generating a virtual driving sound to increase TNR_{order} of the high order. (Otherwise, the dynamic feeling is improved through the powerful feeling is improved by generating a virtual driving sound to increase TNR_{order} of the half order.)

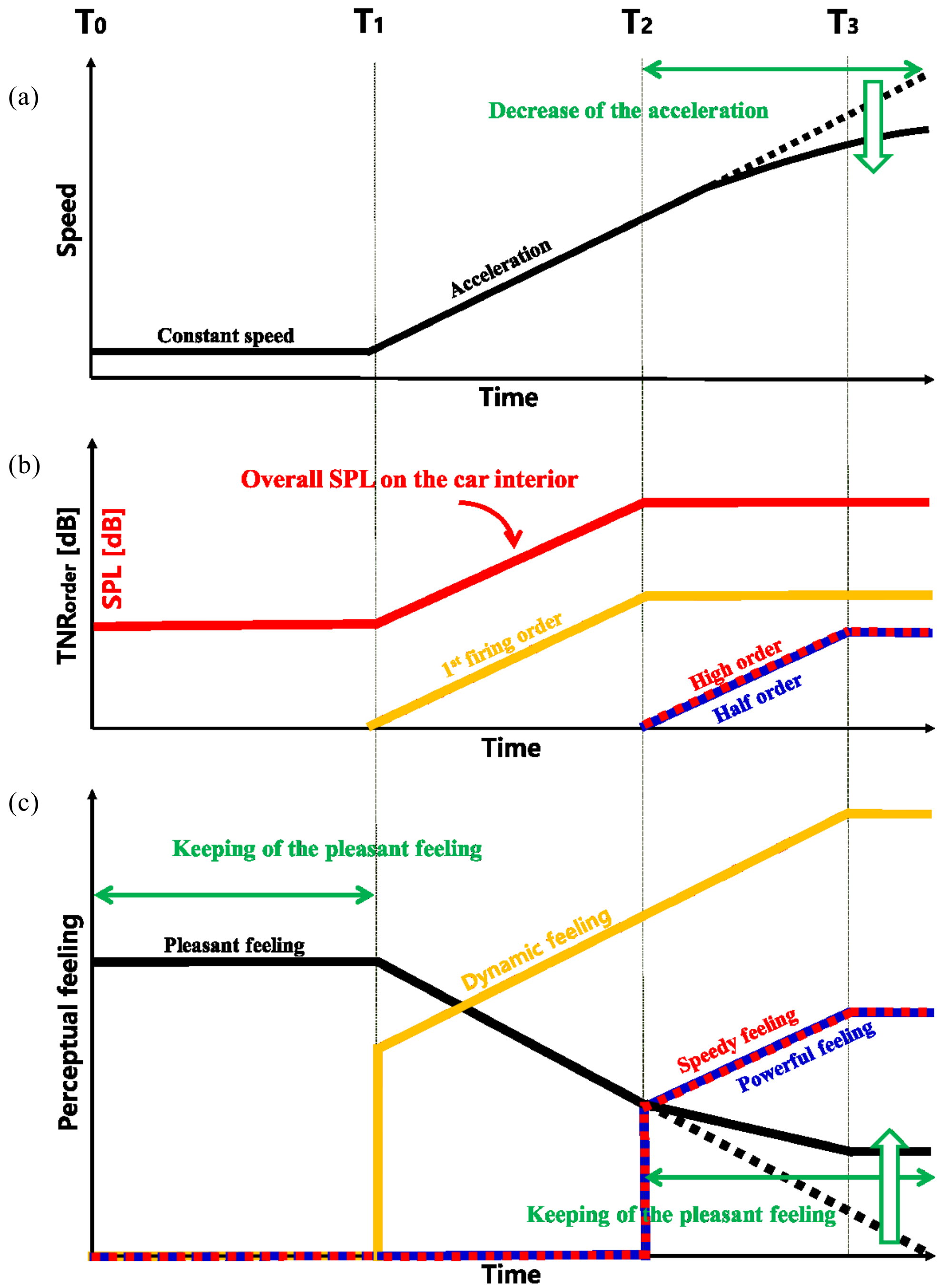


Figure 8 – Strategy generating virtual driving sound

(a) Speed vs. Time, (b) TNR_{order} vs. Time, (c) Perceptual feeling vs. Time

6. CONCLUSIONS

In the study, TNR_{order} was suggested as the acoustic factor reflecting the dynamic feeling of engine sound and, in use of the suggested TNR_{order}, it was known the reinforcement of SPL for the engine sound at the initial acceleration section and the change of tone color for the engine sound at certain section during acceleration were effective for the dynamic feeling enhancement.

Based on these results, the strategy of generating the virtual driving sound was suggested that the dynamic feeling can be improved by generating the virtual driving sound at the specific acceleration condition such as passing drive. In addition, the pleasant feeling can be kept when the virtual driving sound was not generated.

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