

A Systematic Approach to Engine Sound Design for Enhancing Sound Character by Active Sound Design

Seonghyeon Kim, Kyoung-Jin Chang, and Dong Chul Park
Hyundai Motor Company

Seung Min Lee and Sang Kwon Lee
Inha University

ABSTRACT

This paper presents a systematic approach to interior engine sound design for enhancing sound character of car interior sound effectively. Nowadays an active noise control technology is widely used in vehicle industry. Particularly, an active sound design (ASD) technique using vehicle's audio system for controlling interior sound due to powertrain has become a general method to improve sound quality or character. The ASD system using speakers has the advantage of creating various sounds relatively easy. In this study, the novel systematic approach is proposed to guide the efficient design of powerful and pleasant acceleration sound by order spectrum analysis. At first, primary attributes of powerful and pleasant sound were analyzed and sound concept was derived. Secondly, the optimal linearity and the level envelope of firing order were derived by subjective evaluation. Next, the engine orders arrangement was analyzed under the aspects of musical harmonic theory on six cylinders engine. The level ratio of harmonious orders for pleasant sound was also evaluated. And the novel powerful index based on booming and rumbling was developed and used for determining powerful sound target set-up. Finally, powerful and pleasant acceleration sound for six cylinders engine were suggested. These sounds have been implemented through the ASD.

CITATION: Kim, S., Chang, K., Park, D., Lee, S. et al., "A Systematic Approach to Engine Sound Design for Enhancing Sound Character by Active Sound Design," *SAE Int. J. Passeng. Cars - Mech. Syst.* 10(3):2017, doi:10.4271/2017-01-1756.

INTRODUCTION

Sound quality of a passenger car is an important factor for improving emotional quality and characterizing the sound identity which is related brand and product identity. So, many studies and researches have been conducted to develop high sound quality [1, 2, 3,4]. However, the traditional approach, i.e. intake, exhaust modification and various passive ways have several limitations in terms of weight increment, cost, fuel efficiency, regulations and etc. So, recently an active approach which is based on vehicle audio system has been implemented to improve and design interior engine sound effectively. In the early day, the active noise control was restrictively applied to reducing interior booming noise in the field of automotive industry [5]. However, according to increment of maturity of control technology, the active sound enhancement technology becomes a general and popular method to improve sound quality and design sound character of vehicle nowadays [6, 7, 8]. The most common method among active sound enhancement technologies is generating engine sound which is related engine order components [8, 9]. Generated sound through audio speaker system is synthesized with natural interior sound. This method is very efficient because it can be

easy to generate sound. However, it can be difficult to create authentic sounds efficiently if there is not enough understanding about attributes of engine sound. In this context, the systematic approach of engine sound design is needed to reduce the trial and error and improve development efficiency.

In this study, the novel systematic design approach was introduced to guide the efficient engine sound design when the active sound enhancement is implemented. Powerful and pleasant acceleration sounds were developed through this systematic approach. Booming and rumbling sensation were analyzed and developed in the form of the booming index (BI) and modulation index (MI) as means to express powerfulness of engine sound [10]. Designed sound was also analyzed in terms of the powerful index which is the regression model between objective and subject analysis consisted of the booming and modulation index [10]. Also, the optimal linearity of firing order and the arrangement of harmonics were derived for pleasant sound. Both designed sounds in this way were implemented using the active sound enhancement system.

POWERFUL AND PLEASANT SENSATION OF INTERIOR SOUND QUALITY IN A PASSENGER CAR

The sound image can be expressed with various sensibilities such as quiet / loud, not annoying / annoying, desirable / not desirable, not booming / booming, pleasant / unpleasant, smooth / rough, racy / not racy, powerful / weak, exciting / boring and etc. These sensibilities can be categorized by powerful and pleasant sensation by the principle component analysis in subjective evaluation researches [11]. These two sensibilities show the specific characteristic feature as shown in Figure A1 [11]. The height of the low frequency mean EOLE (Engine Order Level Envelope) is related to pleasantness. And steep increment of the EOLE in the low rpm (1000 ~ 2500) area is related to powerfulness. Through such above research case, we can see that powerful and pleasant sensations are affected by the characteristics of engine orders. Also, we can assume that we can effectively design and characterize sound properties via the feature adjustment of the engine harmonic orders.

SOUND DESIGN FOR POWERFUL ACCELERATION SOUND

In order to design the engine acceleration sound that can arouse powerful sensation, the objective and subjective study were carried out in the same order as shown in Figure 1. First, several attributes of powerful sensation were analyzed through previous researches and experiences. Next, the powerful index which is consisted of the booming and the modulation indexes were analyzed. And harmonic order's level profiles were designed to fit into the area that meets the powerful index. Designed engine orders were examined the threshold of that level in order to check the suitability.

Attributes of Powerful Sensation

Through past researches and experiences, powerful sensation of engine sound during acceleration was briefly characterized as follows.

- Proper booming sound at low rpm can be felt dynamically
- Excessive rumble noise at low rpm can be felt engine power or performance is not good.
- Rumble noise from middle to high rpm can be felt good acceleration feeling.
- The harmony of appropriate booming and rumble sounds induces dynamic feel and sportiness.

As appropriate harmony of booming and rumbling sensation of sound is needed to design the powerful engine sound, the powerful index which can judge the powerfulness have been developed.

Basic Conceptual Design

Based on above basic attributes of powerful sound sensation, the conceptual order design can be implemented. The conceptual order design carried out through orders level profile setting: a firing and its harmonic orders which corresponding booming sensation and half order corresponding rumbling sensation. Figure A2 shows the result

of designed order level profiles for V6 type engine sound. In Figure A2, blue color means the conceptually designed level profile and red color means original sound.

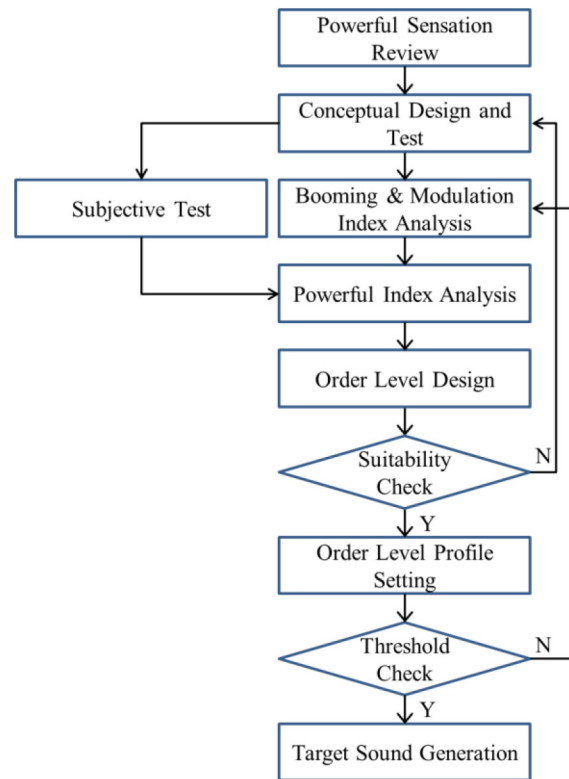


Figure 1. The flow chart for designing powerful acceleration sound

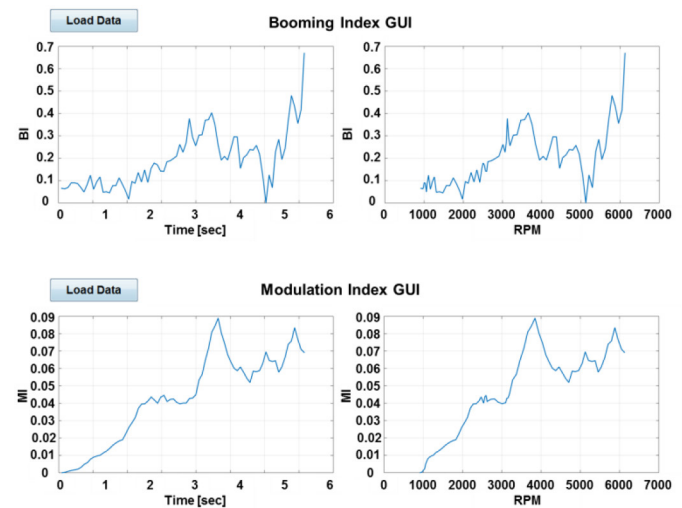


Figure 2. Example of calculation result using developed GUI tool which can calculate the booming and modulation index according to time and engine RPM

Powerful Index Analysis using the Booming and Modulation Index

The booming and modulation index has been developed in the companion paper [10] as a metric for expressing booming and rumbling sensation of accelerating engine sounds. The booming index can be used to calculate the booming intensity according to engine rpm as shown in Equation 1.

$$BI = \frac{1}{100} (25 + 1.2 \times \Delta p) \times \left[1 + 0.9 \left(\frac{f}{1200} - \frac{1200}{f} \right)^2 \right]^{-0.5} \quad (1)$$

Where, Δp means the difference of sound pressure level and f means frequency. Also, rumbling sensation was calculated using the modulation index according to engine rpm. Two indices can be calculated on a time or engine rpm axis using developed calculation GUI tools as shown in Figure 2. The designed sound and sounds of reference vehicles can be objectively compared from the viewpoint of booming and rumbling through this GUI tools effectively. Next, the conceptually designed sound as described in the previous section and reference vehicle's sound were analysis by the booming and modulation index. Figure 3 and 4 depicts analysis results. The sound A represents conceptually designed sound as described in the previous section. And the sound B, C and D represents reference vehicles' sound.

After the objective analysis of acceleration sound using the BI and MI, the subjective jury test for powerful sensation was then carried out. The rating test was applied by twenty people who are the NVH expert and vehicle engineer. The age's range of juries is from 20 to 50 years. Next, the regression analysis was carried out using the result of objective analysis that is calculated by the booming and modulation index and subjective jury test. Through this regression model, the sound quality index was developed for powerful sensation as shown in Equation 2.

$$\text{Powerful Index} = \alpha \times BI + \beta \times MI + \gamma \quad (2)$$

Where, α , β and γ means constants of regression model. The BI means the booming index and the MI means the modulation index. The powerful index is a total of 10 points. In the powerful index, 2 to 4 points indicate quietness; 4 to 6 means mild; 6 to 8 means powerful; 8 to 9 means noisy and 9 to 10 means very noisy sensation. Therefore, the interval between 8 points at 6 points can arouse the powerful sensation. Figure 5 depicts calculation results of the powerful index.

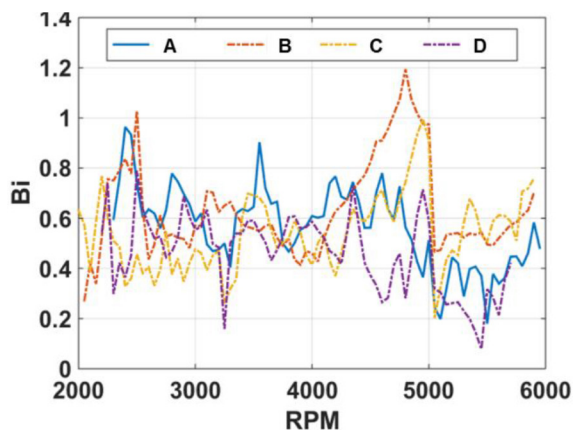


Figure 3. Booming index of analyzed sounds according to engine speed

The sound A, B, C represents reference vehicles' sound and the sound D represent conceptually designed sound. The sound D shows the high score of powerful index from 3000 to 4000 rpm and from 4500

to 6000 rpm. The reason for the high score around 3500 rpm is due to the high score of BI. Also, the reason for the high score from 4500 to 6000 rpm is the effect of MI.

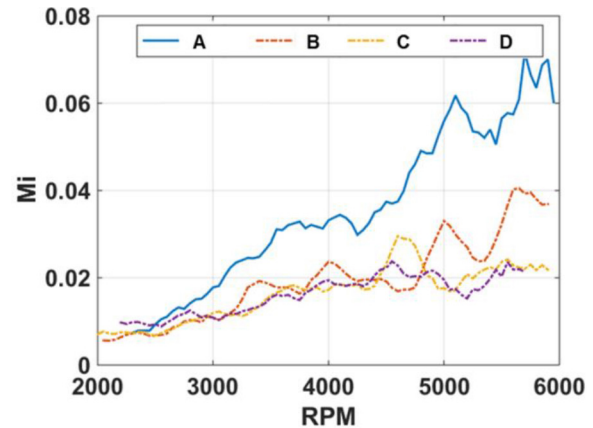


Figure 4. Modulation index of analyzed sounds according to engine speed

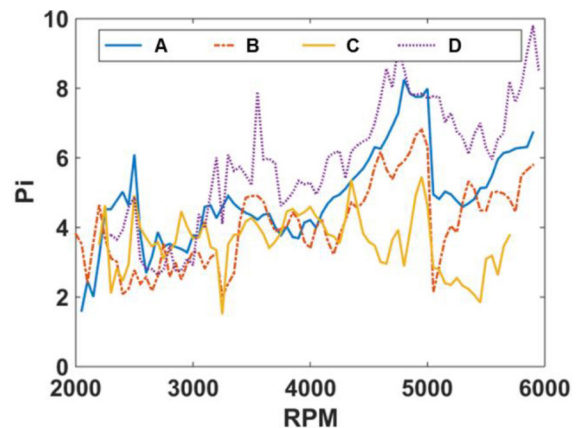


Figure 5. Result of the powerful index calculation about reference vehicle's sound (A, B, C) and conceptually designed sound (D)

Sound Design for Powerful Acceleration Sound

To the next step, various order's level profiles had designed which can include in powerful zone (6 ~ 8) based on powerful index calculation. It was based on the previous conceptually designed sound. Because the power index is composed of the booming and modulation index, the order level profile which is consist of firing order, its harmonics and half orders is configured to find proper booming and modulation values that match the powerful range and to match it. Five acceleration sounds were designed from this concept. The sound source was created by subtracting the order component from the original data and synthesizing the designed order component again. Features of the designed sounds were characterized by booming sensation based on firing order in the low engine speed in order to improve the good acceleration feeling when the vehicle started. And it also characterized by the appropriate combination of booming and rumbling from middle to high engine speed range. And the modulation index was increased in order to arouse a more powerful feeling in the high speed range. Figure 6 and 7 depicts the booming and modulation index according to engine revolution speed each designed five sounds.

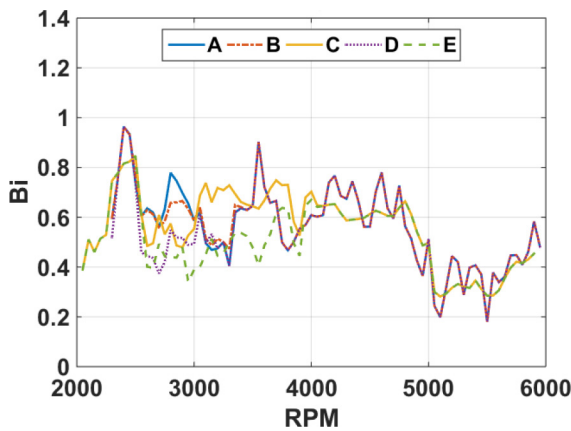


Figure 6. Booming index of designed five kinds of engine sounds according to engine revolution speed

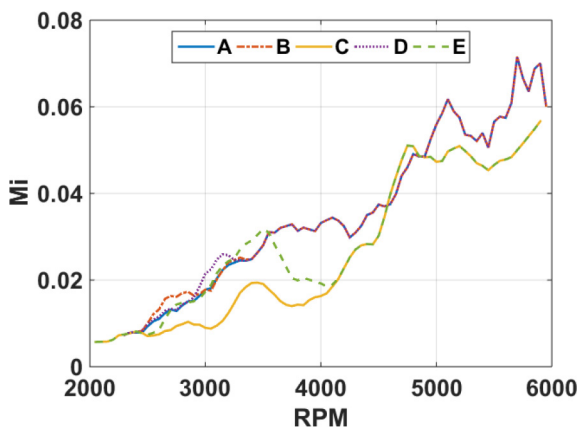


Figure 7. Modulation index of designed five kinds of engine sounds according to engine revolution speed

Next, the powerful index was derived according to engine revolution speed by calculating the each index value to the regression model as shown in Figure 8. Each designed sounds shows similar trends in the analysis of powerfulness. This is a deserved result because we designed engine order's level profile based on BI and MI. However, although characteristics of BI and MI are similar, the preference for sound quality varies from person to person, so subjective evaluation was conducted. So, the final target sound among the five design candidates was determined by the subjective evaluation. The rating test was applied by twenty people who are the NVH expert and vehicle engineer. Ages range of juries from 20 to 50 years. The evaluation was performed on a 7 point scale. The lowest point (1) indicates weakness and the highest point (7) means powerful sensation.

Figure 9 shows the evaluation result. The correlation coefficient between subjective rating and powerful index is 0.96. And the regression analysis results are shown in Equation 3. The R^2 , means coefficient of determination of regression model, value of regression model is 0.928.

$$\text{Subjective rating} = 2.69 \times \text{PI} - 11.7$$

(3)

The subjective evaluation results were in the order of D, A, B, C, E. In the case of C and E, since the value of powerful index is also low because the modulation value was set to low respectively at a low engine revolution speed. So the subjective evaluation score is also low.

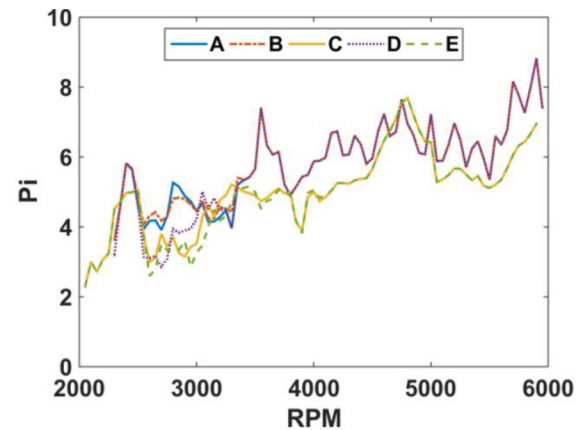


Figure 8. Powerful index of designed five engine sounds according to engine revolution speed

Range Check of Created Order Level and Target Generation

Designed order levels were created within the range of the powerful index through signal processing of wave files. So, when the proposed order level profile is applied to the active sound enhancement system, it can bring about excessive volume that is not matching with the original sound volume range.

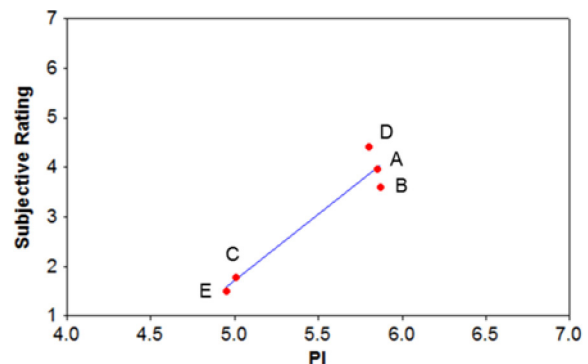


Figure 9. Subjective test result about five designed sounds

And it can also bring out artificial feelings. Therefore, the sound level range analysis was performed on the proposed order levels. Acceleration engine sounds of the vehicle corresponding to the same engine type were analyzed in order to check the level range which can verify the suitability of order level. Order analysis was conducted to analyze the level distribution of orders according to rpm. The average and distribution of order levels were analyzed. Using this way, it can be determined whether the generated level is within the range of actual interior sound. If order levels are larger than the range, it can adjust by offsetting. Figure 10 depicts the result of threshold check about sound D according to each engine revolution speed. The overall order level is exceeded the statistical range at 3000 rpm. In this case, the order level adjusted to within the range can prevent an artificial feeling of generated engine sound. Figure 11