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Active design of a target sound to achieve the desired sound quality inside a car cabin

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ABSTRACT

This paper presents a novel method to design and generate a target interior sound to achieve the desired sound qualities of "powerfulness" and "pleasantness" inside a car cabin. A powerfulness index and pleasantness index were developed to evaluate the perceptions of interior sound based on three sound metrics: booming sensation, rumbling sensation, and the order decay ratio of the recorded interior sounds. The indexes were used for subjective evaluation of a designed target sound. An active sound design (ASD) device with an optimal weighted adaptive order filter was employed to control the magnitude and phase of the sound order related to the engine's revolution speed. A designed target sound with the desired sound quality was generated by the ASD device, which can also actively cancel out unwanted noise in a passenger car. Guidelines to design a target sound are proposed, and the way that the ASD device generates the target sound is presented. An example of the design and generation of a target sound inside a car cabin is also presented.

Keywords: Active sound design, Sound quality, Rumbling index, booming index, Order decay ration, Target sound

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1. INTRODUCTION

The quality of interior sound in a car cabin can be described in terms of "powerfulness" and "pleasantness" (Bisping, 2017). Traditional design methods to make the interior sound powerful and pleasant are based on structural design modifications of the car body. However, it is difficult to use these methods because of limitations such as weight and fuel efficiency. Recently, active sound design (ASD) technology has been employed to design interior sound in real time easily using a car's audio system (Kim et al., 2017; Lee et al., 2017). However, to generate a powerful or pleasant sound inside a car cabin, it is necessary to design the target sound. Therefore, indexes are required to evaluate the perception of powerfulness and pleasantness for the designed target sound.

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The designed target sound should be emitted inside the car cabin in real time using an ASD device. tio (ODR) of a sound from the spectrum analysis (Kang et al., 2015; Borch and Sundberg, 2015). To develop a powerfulness index and pleasantness index, sound metrics should be identified to represent the powerful and pleasant sensations of a target sound. A powerful interior sound can be obtained from a combination of low-frequency booming sound and frequency-modulated rumbling sound (Lee, 2008). Pleasant sound can be expressed by the order decay ratio.

2. THREE SOUND METRICS

2.1 Booming Index

According to Zwicker's empirical data, the relative difference in the pitch effect is linearly proportional to the difference in sound pressure level between the order of booming sound and its side orders. The relative difference of the pitch effect increases as the frequency increases, and the maximum value occurs around 1200 Hz (Zwicker and Fastl, 1999), as shown in Fig. 1. Terhardt et al. presented a similar model (Terhardt, 1982). However, in this model, the maximum pitch effect occurs at 700 Hz. Moreover, the sound pressure level is not linearly proportional. Therefore, we modified this model to fit our results which is the subjective evaluation of the several of car sounds. Considering the pitch effect, the booming index was developed as follows (Lee and Lee, 2017):

$$Bi = \frac{1}{100}[25 + 1.25 \cdot \Delta p] \cdot \left[1 + 0.7 \left(\frac{f}{1200} - \frac{1200}{f} \right)^{2} \right]^{-0.5} \tag{1}$$

2.2 Modulation Index

Rumbling sound can be evaluated objectively by using the modulation of interior sound (Lee, 2008). The sound quality of the rumbling sound also correlates with the roughness of the interior noise (Janssens, 2007). Roughness correlates with the weighted form of the modulation of a sound (Zwicker, 1999), which can be used to evaluate the rumbling sound. The modulation of interior noise was calculated as follows based on the harmonic orders of the rotation frequency of the crankshaft. Fig. 3 shows the systematic process for calculating the modulation index of the interior sound.

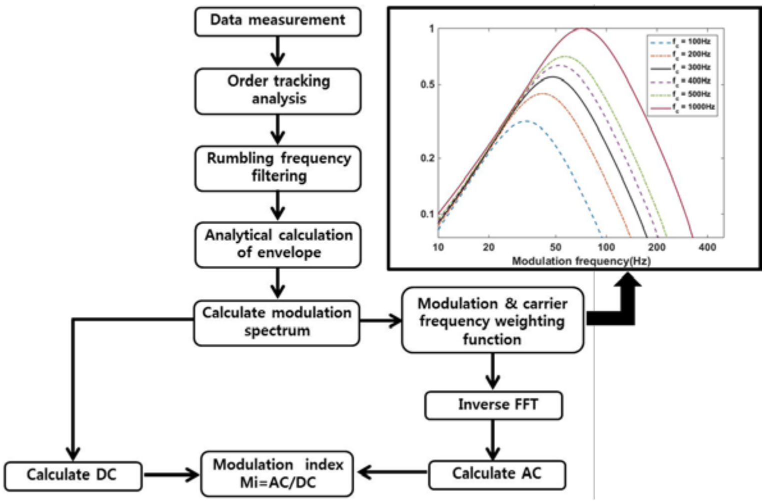

Figure 3. Flow chart of the calculation of the modulation index of interior sound and weighting function for the modulation frequency and carrier frequency.

2.3 Order Decay Ratio

In automotive applications, the frequency bandwidth between integer harmonic orders corresponds to the octave band in the frequency domain. A new sound metric was developed based on the order components of the engine called the ODR. The ODR is calculated through the following procedure. First, the sound pressure levels of the target order and the next two harmonic orders are extracted from the order analysis. For example, in the case of an in-line four-cylinder (I4) engine, if the target order is the 2nd order, the other two harmonic orders are the 4th order and the 6th order. In the case of a six-cylinder V (V6) engine, if the target order is the 3rd order, the other two harmonic orders are the 6th order and 9th order.

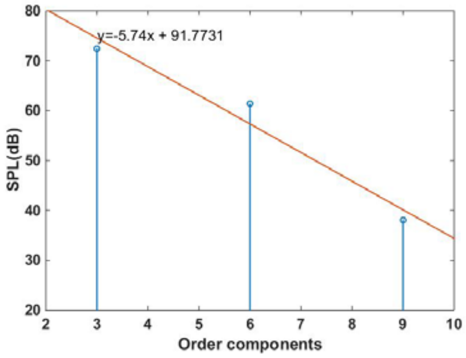

Figure 4. The slope calculated from the three extracted order components.

Secondly, the decay ratio of the sound pressure level per order is calculated using the three extracted order components, as shown in Fig. 4. Finally, the ODR is calculated as the product of the absolute value of the decay ratio and the target order number. This process can be expressed mathematically as follows:

$$\begin{aligned} y &= p_1 x + p_2 x \\ ODR &= p_1 \times \text{ the number of traget order} \end{aligned} \tag{2}$$

where p_1 is the slope calculated from the three extracted orders, and p_2 is an intercept of y.

3. ACTIVE SOUND DESIGN SYSTEM WITH OPTIMAL FILTER

The unwanted noise should be reduced to actively generate a new designed sound with powerful and pleasant sensations inside the cabin of a car, and the designed sound should be emitted inside the cabin. Active noise-cancellation (ANC) systems are used to reduce unwanted noise, and an active sound generation (ANG) system is used to generate the desired sound. Fig. 5 shows the ASD system, which includes an ANC system and ASG system (Rees and Elliott, 2006; Kuo *et al.*, 2007; Oliveira *et al.*, 2009; Lee, 2018). The ASG system has a lookup table containing information on the amplitude of the order components for the designed sound $d(n)$. The target sound $t(n)$ of each order in the ASG system is calculated by multiplying the designed sound $d(n)$ by a reference $r(n)$, as shown in Fig. 5. To generate the designed sound in real time, the amplitude of the reference signal $r(n)$ should unit at any engine speed. The amplitude of the target sound $t(n)$ multiplied by the reference $r(n)$ with unit amplitude becomes the same as that of the designed sound $d(n)$

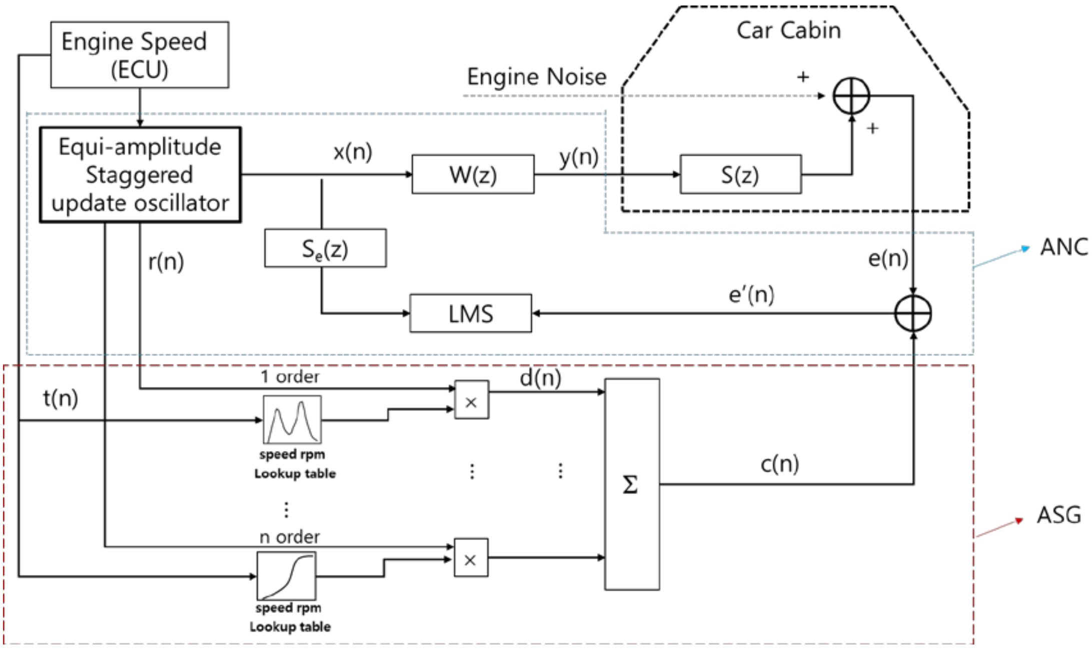

Figure 5. Active sound design system based on an adaptive filter with optimized weights.

According to previous research and experience [1], the characteristics of powerful sound are as follows:

- Proper booming sound at low speed results in a dynamic perception by the passenger.

- Loud booming sound at a specific speed (causing structural resonance) results in the perception of a very loud by the passenger.
- Excessive rumble sound at low speed can reduce the perception of powerful performance of the vehicle.
- Rumble sound during acceleration of the vehicle from middle speed to high speed gives the passenger a perception of powerfulness with high performance.
- The appropriate harmony of booming sound and rumble sound induces the perception sportiness and powerfulness. The powerfulness index was employed to design a powerful sound. The first purpose of the sound design is to find a quiet area where a powerful sound should be implemented by adding booming and rumbling sound, or a noisy area where the booming sound should be reduced. Finally, the powerfulness index should be applied to the designed sound to estimate the subjective rating of powerfulness.

4. CONCLUSIONS

Please follow these manuscripts preparation instructions carefully. A novel method to design a target sound for interior sound was proposed based on a powerfulness index and pleasantness index. These indexes are useful for the estimation of subjective ratings for the powerfulness and pleasantness of interior sound. To design a powerful and pleasant target sound, sound metrics are needed to represent the relationship between the target sound and the perceptions of powerfulness and pleasantness. The booming index, modulation index, and ODR were developed as sound metrics. Using these metrics, guidelines for the design of a target sound were presented. An ASD device was used to generate a target sound inside a car cabin. The OW-FxLMS algorithm was used to control the magnitude and phase of the sound order since the three sound metrics are related to the magnitudes of the order components of interior noise. An example was presented for the design of a target sound and the generation of the sound inside a car cabin using the ASD device. The proposed method could be useful for controlling the sound quality of interior noise.

5. ACKNOWLEDGEMENTS

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