

A Novel Method for Objective Evaluation of Interior Sound in a Passenger Car and Its Application to the Design of Interior Sound in a Luxury Passenger Car

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ABSTRACT

Recently the interior sound is actively generated by the active sound design (ASD) device in a passenger car. Therefore, the objective evaluation method for the sound quality of actively designed sounds is required. In previous research, the sound quality of interior sound has been presented with powerful and pleasant for the existing passenger car. This paper presents a novel approach method for the objective evaluation of powerfulness and pleasantness of actively designed interior sound. The powerfulness has been evaluated based on the degree of modulation and a quantity of low frequency booming of the sound in the paper. On the other hand, the pleasantness is evaluated based on the slope ratio of harmonic orders per octave in frequency domain. These evaluation methods are successfully applied to the objective evaluation of luxury passenger car. The sound with powerful and pleasant character is designed based on these two evaluation parameters and employed to the interior sound of a new luxury passenger car.

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INTRODUCTION

In previous research, the sound quality of interior sound has been presented with powerful and pleasant for the existing passenger car [1]. It is practically impossible to make the interior sound powerful and pleasant with the traditional design method based on the structural design of a car body because there are many limitations such as weighting and fuel efficiency. Recently ASD technology has been employed to design the interior sound because it is easy to design and to generate the interior sound that the customers prefer with just audio sound system [2]. However, the sound metric to express the powerfulness and pleasantness is necessary for the design of the sound with these sensations. The previous studies show that the booming sensation and the rumbling sensation are correlated to the sound quality of interior sound [3, 4] and the ratio of spectrum decay is correlated to the pleasantness of the horn sound and the music sound [5, 6]. The spectrum decay means the decay ratio of the sound pressure level per octave frequency. In automotive application, the decay ratio of sound pressure level per integer order can be used similarly. The booming sound is related to the sound pressure level of

the interior sound and its frequency. Rumbling is related to the modulation of the interior sound. Therefore, in the paper, not only the booming index (BI) and modulation index (MI) are developed as the sound metrics of powerfulness and applied to the development of powerful index but also the ratio of order decay based on the spectrum decay is developed as the sound metric of pleasantness and applied to the development of pleasant index of a vehicle. Based on these results, systematic way to enhance sound character of interior engine sound will be introduced in the companion paper [11].

BOOMING INDEX

During acceleration and deceleration of a vehicle, a powerful tonal sound with low frequency less than 250 Hz occurs inside of cabin. This sound is called "booming sound" [3]. The booming sound is a vibro-acoustic sound caused by the resonance between the structure-vibration modes and cavity modes of a car. The sensation of the booming sound is perceived as a dynamic sound or powerful sound because it compresses the passenger's ear with high sound pressure

level. However, if the sound pressure level is too high, the interior sound is perceived as an annoyance car while the interior sound of a car without booming sensation is perceived as a quiet car. Therefore, the booming sound with proper sound pressure level is required to obtain the powerful sensation or dynamic sensation [1]. The perception of tonal sound such as a booming sound is changed depending on the frequency. If the frequencies of two tonal sounds with the same sound pressure level are different each other, the perception for these sounds are different. Fig. 1 shows the pitch effect. All tone signals shown in Fig. 1 have the same sound pressure level of 80dB but the frequencies are different. Despite all signals have the same sound pressure level, people feel differently depending on the frequency. This different perception is due to the pitch effect of a tonal sound [7, 8]. Therefore, there are two major factors for the control of the perception for booming sound. One is the deference between the sound pressure level of the order component associated with a booming sound and that of its side orders, the other one is the frequency of the booming sound.

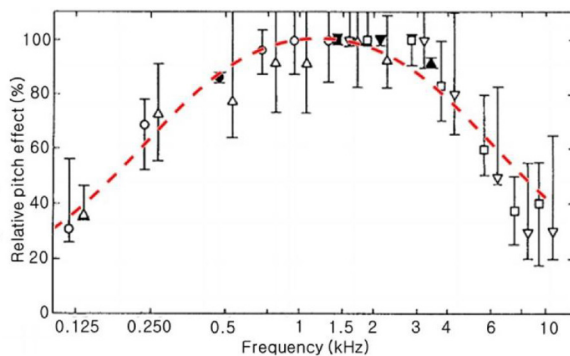


Figure 1. Comparison of relative pitch effect of pure tones at 80 dB sound pressure level.(bar) Zwicker's empirical data; (- - -) pitch effect model.

According to the Zwicker's empirical data [8], the relative difference of the pitch effect is linearly proportional to the difference of sound pressure level between the order of booming sound and its side orders. The relative difference of the pitch effect increases as the frequency increase and arrives to its maximum value around 1200Hz [8] as shown in Fig. 1. A similar model to this result exists in Ref. 7. However, in this model, the maximum pitch effect is at 700Hz. Moreover, the sound pressure level is not linearly proportional. So we modified this model to fit our results. With considering the pitch effect, the booming index is developed and given mathematically by

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

where Δp is the difference of sound pressure level and f is frequency. The algorithm to realize the booming index is developed based on Eq. (1) and the flow chart is shown in Fig. 2. According to this process, we can obtain the booming index of the interior sound if we input the sound file to this algorithm.

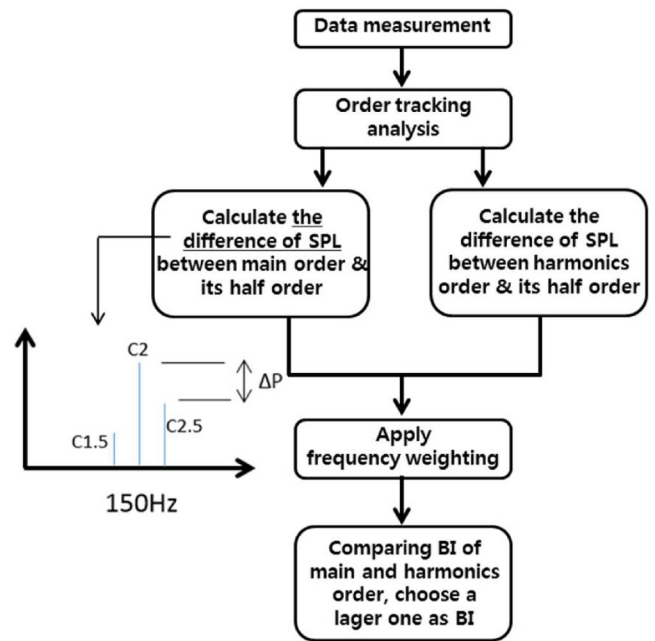


Figure 2. Flow chart of the calculation of the booming index of interior sound.

MODULATION INDEX

The rumbling sound is caused by the bending vibration and torsional vibration of the crankshaft which is excited by the combustion force when the fuel of the engine is fired. The combustion force has a little variation among cylinders. The vibration of the crankshaft is transferred to the interior sound as a structure-borne sound. Therefore, the rumbling sound is caused by the resonances of the structures on the way of transfer path from the engine to car body. There are many resonance frequencies between 200 Hz and 500Hz due to the resonance of the transfer path. The frequency bandwidth of the resonances is wide and this is not a tonal sound. The rumbling sound includes a number of frequencies and is the amplitude modulated sound because the amplitudes of each frequency within bandwidth are difference each other. The rumbling sound can be evaluated objectively by using the modulation of interior sound [3]. It is known that the sound quality of the rumbling sound is correlated to roughness of the interior noise [9]. Roughness is correlated to the weighted form of the modulation of a sound [8]. The rumbling sound can be finally evaluated by using weighted modulation of the sound. In this paper, the modulation of interior noise is calculated based on the harmonic orders of the rotating frequency of the crankshaft as follows [10]:

- Step 1. Order tracking analysis. Calculate the amplitude, the phase, the frequency of harmonic order components for the measured interior sound at each rotating speed (rpm) of the engine. The order data is extracted from 0.5 order to 10 order by 0.5 order interval. Because the maximum frequency of the rumbling sound is about 500Hz, it is unnecessary to use an order of more than 10 orders.

- Step 2. Filtering. The calculated order data are filtered by the bandpass filter. The frequency range of the band pass filter is from 200Hz to 450Hz.
- Step 3. Calculate the envelope of the filtered data. The envelope of the filtered signal is calculated by using Eq. (2).

$$D_1 = A_1^2 + A_2^2 + A_3^2 + A_4^2$$

$$C_1 = 2A_1A_2 \cos(2\pi(f_2 - f_1)t + (\varphi_2 - \varphi_1))$$

$$+ 2A_2A_3 \cos(2\pi(f_3 - f_2)t + (\varphi_3 - \varphi_2))$$

$$+ 2A_4A_1 \cos(2\pi(f_4 - f_3)t + (\varphi_4 - \varphi_3))$$

$$C_2 = 2A_1A_3 \cos(2\pi(f_3 - f_1)t + (\varphi_3 - \varphi_1))$$

$$+ 2A_2A_4 \cos(2\pi(f_4 - f_2)t + (\varphi_4 - \varphi_2))$$

$$C_3 = 2A_1A_4 \cos(2\pi(f_4 - f_1)t + (\varphi_4 - \varphi_1))$$

$$\text{envelope}(t) = \sqrt{D_1 + C_1 + C_2 + C_3}$$

(2)

where A_i is the amplitude, f_i is the frequency, and φ_i is the phase of i -th order.

- Step 4. Spectra of envelope. Calculate the spectrum of the envelope of filtered data. In this spectrum, the value at 0Hz is called the DC component. The DC value will be used at step 6.
- Step 5. Calculate the spectrum of the envelope weighted by the weighting function. According to theory of roughness [8], the more the modulation frequency is close to 70 Hz and the carrier frequency approaches at 1 kHz, the more the sound is rough. The weighting function of modulation frequency and carrier frequency is illustrated as shown in Fig. 3.
- Step 6. Calculation of the weighted modulation. Applying the weighting function of the step 5 and transformed it into the time domain from the spectrum domain by taking inverse Fourier transform. The root mean square value for this transformed data is called AC. The modulation index can be calculated by dividing the AC value by the DC value calculated in the step 4.

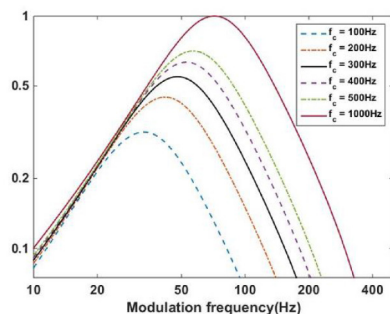


Figure 3. Weighting function for modulation frequency and carrier frequency.

The systematic process for the calculation of the modulation index for the interior sound is presented as shown in Fig. 4.

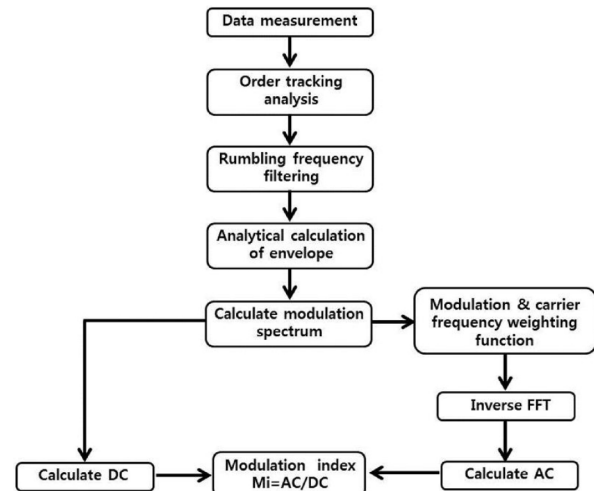


Figure 4. Flow chart of the calculation of the modulation index of interior sound.

ORDER DECAY RATIO

Generally, in interior sound of the vehicle, the pleasant sensation tends to be decreased when the powerful sensation increases. Although the two sensations are not exactly in inverse proportion, it is evident that there is a trade-off between pleasantness and powerfulness [1]. Therefore, the relationship among booming index modulation index and pleasant sensation is investigated with the subjective evaluation. According to this investigation, it is found that the booming index is not low correlation with pleasantness and the modulation index is inversely correlated with pleasantness [9]. However, the modulation index is not enough to represent pleasantness alone for the objective evaluation. The spectrum decay method is employed for the objective evaluation of the pleasant sensation. The ratio of spectrum decay means the decay ratio of the sound pressure per octave frequency [5]. In automotive, the integer harmonic orders are the octave frequencies based on the spectrum decay, a new sound metric is developed based on the order components of the engine and it is called “order decay ratio (ODR)”. The ODR is calculated through the following procedure. At the first, the sound pressure levels of target order and next two harmonic orders are extracted from the order analysis. For example, in case of in-line four cylinder (I4) engine, if the target order is the 2nd order, other two harmonic orders are the 4th order and the 6th order. In case of the vee six cylinder (V6) engine, if the target order is the 3rd order, other two harmonic orders are 6th order and 9th order. Secondly the decay ratio of the sound pressure level per order is calculated using three extracted order components. Fig. 5 shows the procedure calculating the decay ratio of the sound pressure level per order of interior sound. 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 and is given by

$$y = p_1x + p_2$$

$$ODR = |p_1| \times \text{the number of target order}$$

(3)