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Development of sound-quality indexes in a car cabin owing to the acoustic characteristics of absorption materials

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ABSTRACT

This study presents a method to predict the quality of sound in a car cabin when the acoustic characteristics of absorption materials in a car are changed. We proposed a signal processing model based on an acoustic ray tracing method to predict the variation of interior car cabin sounds corresponding to changes in the acoustic absorption material attached to the sidewall of the engine room of a virtual car. The interior sounds corresponding to seven different acoustic materials were simulated using this model and were recorded inside of a virtual car. The predicted interior sound was compared with the recorded interior sound. The recorded interior sounds were used to develop a sound quality index estimating the variation of sound quality owing to the change in acoustic materials. The sound quality index was developed in terms of sound metrics correlated with subjective evaluation of the recorded interior sounds. The sound metrics were investigated based on psychoacoustic parameters and the acoustic properties of the absorption materials. Finally, the proposed method was validated with real car by experiments. The proposed method can be used for the prediction of the variation of sound quality of interior sound owing to changes in the acoustic materials at the early car-design stage and thus aid in the selection of the optimal acoustic material in view of car weight reduction.

1. Introduction

There are various sounds inside the cabin of a car such as road sounds, wind sounds, and engine sounds [1]. Much research has been conducted on these noises and these studies have effectively reduced noise levels. Recently, research on the sound quality of automobiles has consisted of the development of various indexes for objective evaluation of sound quality in a car and the improvement of sound quality using these indexes [1]. Typical sound-quality indexes include a booming index, a rumbling index, a tire sound index, a gear whine sound index, and others [2,3]. In recent years, studies have been performed on the optimization of acoustic absorption materials to improve the sound quality of a car based on ray method [4]. However, there is still a shortage of research on the evaluation of the quality of the interior sound owing to the characteristics of acoustic absorption materials. The purpose of this study was to develop a sound-quality index of absorption material (SQIAM) to objectively evaluate the influence of acoustic absorption materials on the quality of the interior sound. To develop the SQIAM, a model predicting the variation of interior sound owing to the change of the sound absorbing material was required. In previous research, to predict the interior sound quality of a car with respect to acoustic absorption material, the finite element method [5] and the boundary element method [6] have been studied. These methods are useful for low-frequency sounds. For middle frequencies, the statistical energy analysis method [7] has been used. At high frequencies, the acoustic ray tracing method provides the highest accuracy [13]. The application of acoustic absorption material is effective to change and reduce the sound pressure of the engine room or inside a car cabin at high frequencies. Therefore, to develop a model to predict the interior sound quality of a car corresponding to the acoustic absorption material, the acoustic ray tracing method [7,8] was used in this study. This prediction model was developed based on the signal processing technique [9] and was used to simulate interior sounds corresponding to different absorption materials attached to the sidewall of the engine room of a virtual car. The interior sounds were recorded inside of a virtual car. The recorded sounds were used to develop the SQIAM. The SQIAM was developed based on the subjective evaluation of the recorded sounds and their sound metrics. A sound metric should be correlated to the subjective evaluation of the recorded interior sound. The sound metrics, psychoacoustic parameters, and acoustic properties of the

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absorption materials were considered for the production of the SQIAM to achieve maximum sound pleasantness and powerfulness. In this study, four sound-quality indexes were developed. These indexes were developed based on the sound metrics and the acoustic properties of the absorption materials. The sound metrics and the acoustic properties correlated with subjective rating were used for the development of these indexes. In Section 5, the development process is presented. For the validation of these indexes in a real car, an experiment was conducted with a sports utility vehicle. These indexes can be useful for the determination of the optimal materials in view of sound quality together with consideration of the reduction of weight and cost of a vehicle in the early design stages.

2. Prediction of interior sound based on signal processing

This section presents the signal processing model to predict the sound inside the cabin of a car emitted by an engine in the engine room of the car depending on the absorption characteristics of the materials attached to the sidewall of the engine room.

Fig. 1 shows the production concept of the model based on the signal processing technique. In this model, the engine was regarded as an acoustic source $q_1(t)$, and the generated sound is propagated to the sidewall of the engine room. The sound hitting the sidewall is reflected and transmitted into the cabin of the car. The pressure p_2(t) of the sound hitting the sidewall of the dash panel of the car can be predicted by convolving the impulse response function (IRF) of the engine room into the volume velocity of the acoustic source. The acoustic source was assumed a monopole source. The dash panel was divided into N number of sections acting as receiving points. The sound pressure p_2(t) can be expressed mathematically as follows:

$$p_{2_i} = q_1 * IRF1_i \tag{1}$$

where q_1 is the volume source of the engine, and i is the i-th airborne transfer path between the engine source and the dash panel as shown in Fig. 2.

The IRF between the acoustic source and the i-th part of the sidewall of the dash panel in the engine room, IRF1$_i$, was numerically calculated by the ray tracing method [8,9]. The IRF1i changed depending on the characteristics of the absorption material attached to the sidewall of the engine room. The pressure p_3(t) of the sound transmitted into the cabin of the car can be obtained by the theory of insertion loss. Assuming that the wave hitting the dash panel in the engine room is a plane wave, the insertion loss of the dash panel is given by

$$\mathrm{IL}(\omega) = 20\log(P_2(\omega)/P_3(\omega)) \tag{2}$$

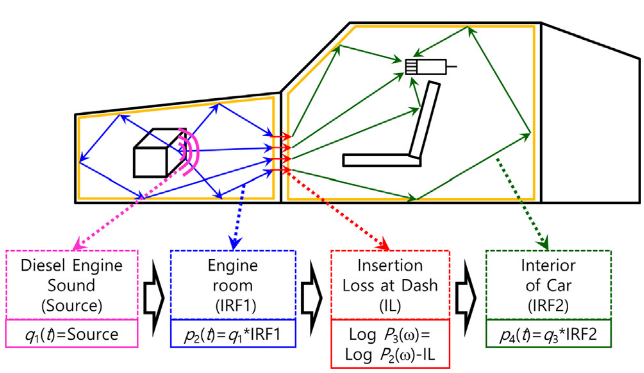

Fig. 1. Prediction model for interior sound based on signal processing.

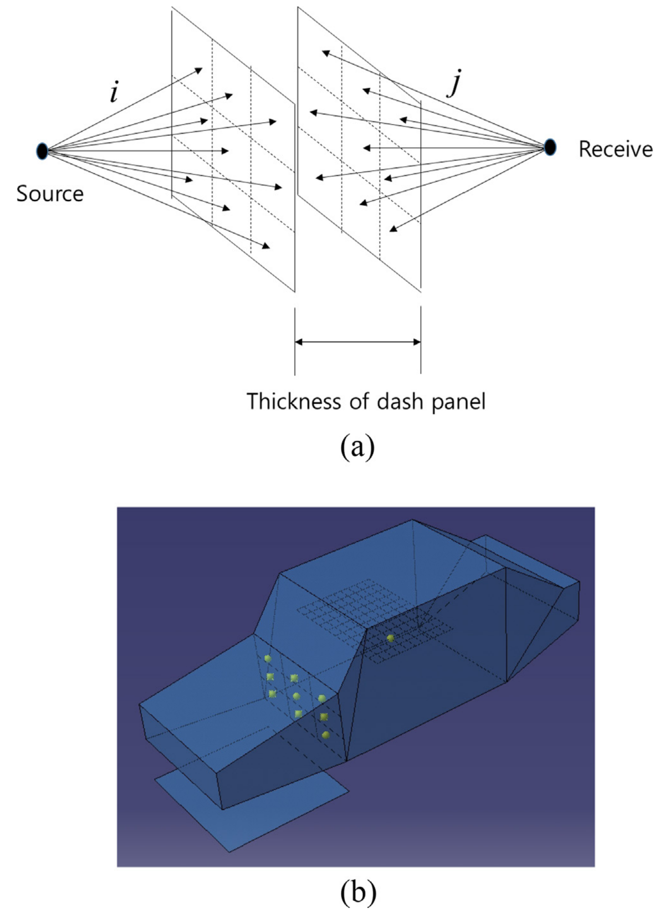

Fig. 2. Part of the dash panel on the airborne transfer path from engine to inside cabin: (a) transfer path of airborne sound, and (b) divided part of virtual car.

where P_2 (ω) and P_3 (ω) are the spectrums of sound pressure $p_2(t)$ and $p_3(t)$, respectively. Because the impedance of the engine room and the car cabin can be expressed by multiplying the air density ρ by the speed of sound c_0, the ratio of sound pressure is given by

$$\left|\frac{P_2(\omega)}{P_3(\omega)}\right| = 10^{\mathrm{IL}(\omega)/20} \tag{3}$$

In general, the insertion loss is measured in the specific acoustic room and has no phase information. Therefore, It have to assume that the phase between $P_2(\omega)$ and $P_3(\omega)$ is a linear delay and the sound pressure $P_3(\omega)$ can be estimated in terms of the magnitude and phase of $P_2(\omega)$. Therefore, the estimated sound spectrum of $P_3(\omega)$ is given by

$$\hat{P}_3(\omega) = |P_3(\omega)|e^{j\angle p_3(\omega)} = \frac{|P_2(\omega)|}{10^{\mathrm{IL}/20}} e^{j\angle P_3(\omega)} \tag{4}$$

where $\angle$ P_3 (ω) is the linear delay of the phase of P_2 (ω). The sound pressure $p_3(t)$ at the sidewall of the dash panel inside the car cabin was estimated by taking an inverse Fourier transform given by

$$\hat{p}_3(t) = ifft(\hat{P}_3(\omega)) \tag{5}$$

The transmitted sound travels inside the cabin and propagates to the ear position of the passenger. The sound hitting the sidewall of the cabin is reflected and absorbed by the acoustic materials of the sidewall. The pressure p_4(t) of the sound hitting the ear of a passenger can be predicted by convolving the impulse response of the cabin into the volume velocity of the acoustic source generated by the vibration of the dash panel. The IRFs between the ear