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Design optimization of a dual-shell car horn for improved sound quality based on numerical and experimental methods

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ABSTRACT

The objective of this article is to describe the design method of a dual-shell car horn (DSCH) with good interior sound quality based on the boundary element method and transfer path analysis (TPA). A prediction model of the perceived sound quality was developed to determine the DSCH's two fundamental frequencies. A boundary element model for the design of a new DSCH was also explored, and the results were applied to a drawing for the implementation of a prototype car horn. To evaluate the interior sound quality during operation of the prototype, an index for estimating the sound quality level is required. The index was developed using the slope of the spectral decay with respect to the frequency in the spectral analysis of interior sound measured inside a car. The effect of the car body on the interior sound quality was also investigated using TPA. The mounting location of the car horn on the body was changed, and the mounting bracket was modified to improve the interior sound quality. The proposed method was successfully applied to design a new DSCH with superior sound quality.

1. Introduction

Advances in automobile engineering technology have increased the customer requirements regarding the sound quality inside automobiles. The quality of sound that is heard inside cars is becoming one of the major factors that determine customers' choices of cars [1–6]. The sound of the car horn is one of the sounds heard while driving a car. The quality of the interior sound due to car horns is one of the factors that affect the sound quality in cars and thus influence customer choice. Additionally, the sound pressure level (SPL) of exterior sound must satisfy international regulation standards. The sound quality of car horns has been studied [7–9]. In Ref. [7], a sound quality index (SQI) based on psychoacoustic parameters was introduced. This index is used in designing new car horns. In these previous studies [7–9], sound was emitted from car horns in a laboratory setting; sound was not measured inside a car. Thus, the researchers did not consider the effects of the transfer function of vehicles. A recent study addressed the interior sound quality of car horns [10]. In that paper, an SQI based on the spectral decay of the interior sound measured inside cars was developed. The spectral decay corresponds to the attenuated SPL per octave in the spectral analysis of the interior sound measured inside a car. The objective of this article is to describe the design method of a new dual-shell car horn (DSCH) that has good interior sound quality. First, a prediction model of the perceived sound quality for determining the two fundamental frequencies (FFs) of the new DSCH was developed on the basis of subjective evaluation of 29 synthetic horn sounds (obtained using a commercial reference horn with good sound quality) and the reference horn sound. Second, the new DSCH was designed using a boundary element method (BEM) to control the two FFs, and a prototype of the new horn was implemented. Third, the transfer paths of horn sound from the mounting location of the car horn outside the car to the driver's location were investigated using the TPA. Finally, the mounting location and mounting bracket of the new DSCH were optimized on the basis of the TPA and the SQI (which was developed using the spectral decay), respectively [10,15]. In order to find the effect of the car body, we investigated two paths such as the structure-borne and airborne paths for car horn sound using the TPA method. Therefore the structure-borne and airborne contributions to interior sound were obtained throughout the TPA. The TPA method was explained in Section 3.

A BEM of a car horn was developed for estimating the acoustic mode shapes and natural frequencies for the acoustic path of a car horn. The choice of mounting location and modification of the mounting brackets were investigated to improve the sound quality of the new DSCH.

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2. Structure and acoustics of car horn

2.1. Structure and operation of a car horn

As shown in Fig. 1, a typical car horn consists of an oscillator and a resonator. The oscillator generates vibro-acoustic sound using an oscillating magnetic field at the coil and the magnetic force between the pole and the armature. The magnetic force pulls and pushes the armature to generate a reciprocating motion, causing the horn's diaphragm to oscillate. The diaphragm's oscillation compresses and dilates the air inside the compression chamber. The resonator amplifies the sound pressure generated by the oscillator and emits the horn sound. The sound pressure is amplified at the natural frequencies of the acoustic modes in the acoustic path of the horn.

2.2. Characteristics of emitted sound

Fig. 2 shows the process of horn sound generation in the spectral domain. In Fig. 2, $X(f)$ is the spectrum of the sound generated by the reciprocating motion of the armature, which is determined by the material properties, thickness, and shape of the diaphragm [11]. The function $H(f)$ is the transfer function of the resonator, which is determined by the shape of the acoustic duct. The function $Y(f)$ is the spectrum of the sound emitted from the horn; it is obtained by multiplying $X(f)$ by $H(f)$. The sound spectrum $X(f)$ is generally harmonic owing to the harmonics of the diaphragm's structural vibration modes. These harmonic components are attenuated as the sound passes through the resonator; however, the resonant frequencies of the resonator are not attenuated. In this work, a DSCH is evaluated. A typical DSCH consist of two shell horns, each of which generates a unique sound and unique spectrum. The spectrum consists of a fundamental frequency and its harmonic components. Therefore, analysis of the car horn sound spectrum reveals that the DSCH has two FFs and their harmonic components. There are international regulation standards regarding the SPL of a car horn sound [12]. It should be between 105 dBC and 115 dBC at a certain distance from the source (2 m from the car horn and 1.2 m from the floor). The SPLs of all the car horns mentioned in this paper meet international regulation standards. The selection of the two FFs is important in terms of the car horn sound quality. Fig. 3 shows spectral analyses performed for nine commercial sample car horns. These sounds were measured in an acoustic room designed for the measurement of car horn sound. The wall of the room is treated with acoustic material. The microphone and car horn were installed 1 m above the floor with a distance of 2 m between them. In the listening test, the sounds were measured using a binaural head. According to a survey of the FFs of the nine horns, most commercial car horns have two FFs between 350 Hz and 600 Hz. According to the results of these spectral analyses, the intervals between the two tones and the spectral slopes of different car horns are different, implying that the sound qualities of the horns also differ. The sound quality of the nine sample car horns was subjectively evaluated. In this subjective test, 41 people (21 men and 20 women, 18–34 years old) listened to sounds emitted by different car horns. All the participants had normal hearing. At the time of the test, about two-thirds of the participants were employed as noise control engineers in an automotive company. One-third of the participants were students who had received training related to car horn sounds. The car horn sound quality was subjectively rated on a scale from 4 to 9 [1], where 4 corresponds to the lowest sound quality, and 9 corresponds to the highest. The questionnaire for the evaluation of the sound quality sought to determine "which sound is the best car horn sound." Fig. 4 shows the mean value and standard deviation of the distribution of subjective ratings of car horn sounds. The type I sample car horn scored highest, as shown in Fig. 4.

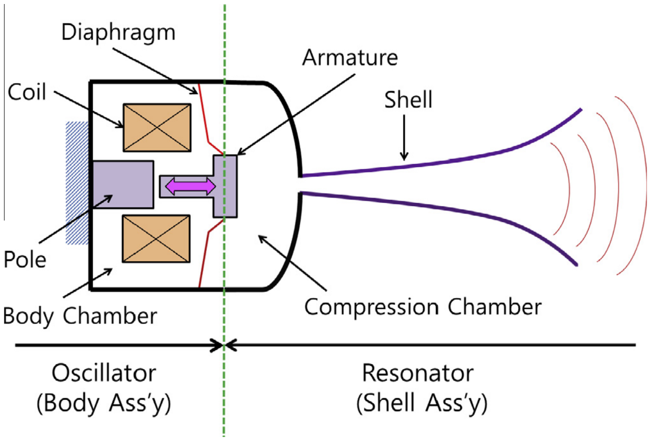

Fig. 1. Structure of a car horn.

2.3. Determination of two FFs for a car horn

To compare the perceived sound quality according to the interval of the two FFs, a range of various DSCH sounds are needed. Therefore, 29 synthetic sounds were designed. The sound of the type I sample car horn was used as a reference sound for the design of 22 of the synthetic sounds because its sound quality was rated the best among the nine commercial sample car horns, as described in the previous section. The two FFs of the reference sound were 420 Hz and 495 Hz. The lower FFs were selected using eight different frequency steps, and the higher FFs were selected using seven frequency steps. The two FFs of these 22 synthetic sounds were selected from among these frequency ranges. In addition to the 22 sounds, 7 synthetic sounds were also designed by considering musical intervals. Two perfectly consonant sounds, three imperfectly consonant sounds, and two dissonant sounds were designed. Overall, 30 sounds (29 synthetic sounds and 1

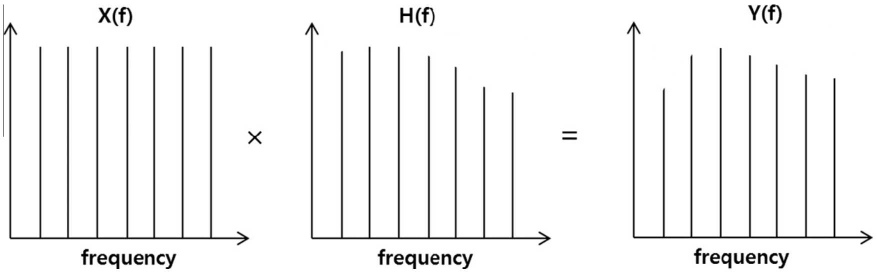

Fig. 2. Generation of interior sound in the frequency domain.