Applied Acoustics 136 (2018) 16–25

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Model of psychoacoustic sportiness for vehicle interior sound: Excluding loudness

Gahee Kwon, Hyeonho Jo, Yeon June Kang*

Advanced Automotive Research Center (AARC), School of Mechanical and Aerospace Engineering, Seoul National University, Seoul 08826, Republic of Korea

ARTICLE INFO

Keywords:
Sportiness
Vehicle interior sound
Sound quality index
Jury test
Regression analysis
Roughness

ABSTRACT

As vehicle interior noise control technology has significantly improved, focusing on vehicle interior sound quality has been suggested recently for improving user satisfaction. Research on the improvement of vehicle interior sound quality can be applied to the design of vehicle interior sound in order to achieve the desired image. For targeting the desired image, however, the subjective assessment of sound quality should be correlated with objective values because only quantitative and measurable data can be used for the control of vehicle interior sound. In this study, a model of psychoacoustic sportiness for vehicle interior sound was developed to target the “sporty” image of vehicles. The interior sounds of various vehicles were recorded under wide open throttle (WOT) acceleration condition, and subsequently modified to obtain additional sound samples. The loudness values of all stimuli were adjusted to the same value for excluding the impact of loudness on sportiness. In order to achieve subjective assessments of sportiness, a jury test was conducted, and sportiness was quantified using regression analysis. Therefore, the model for psychoacoustic sportiness was determined as a function of roughness, sharpness, and tonality. In a validity study, the sportiness estimated by this model was consistent with the observed sportiness of the additional jury test. Consequently, it was suggested that the sportiness model proposed in this paper is reliable and can be applied practically because the effect of loudness was excluded.

1. Introduction

Recently, research on the enhancement of vehicle interior sound quality has been widely conducted in order to improve user satisfaction. Since the total elimination of noise and vibration in a vehicle is not always achievable, vehicle interior noise still exists even after noise control. Consequently, enhancing the quality of vehicle interior sound has attracted increasing attention [1,2]. The research on improving vehicle interior sound quality has reached a new level, i.e., sound design. Chang and Park proposed a target sound design method based on musical instruments and a speech production mechanism in order to represent the concept and brand image of a vehicle by using the driving-sounds of gasoline-powered vehicles [3]. Moreover, Engler developed a sound generation system for electric vehicles (EVs) [4]. Engler attempted to design well-balanced interior sound for EVs and also emphasized the powerfulness of sound using three types of sound-synthesis filters: order-synthesis, wavelet-synthesis, and granular-synthesis. Therefore, if researchers wish to develop vehicles in accordance with the desired image, they can concentrate on the sound quality in addition to the exterior design or engine performance.

In order to control and enhance sound quality, however, researchers must correlate the results of subjective assessment with the results of objective measurements for reliability. In other words, researchers who wish to evaluate, measure, and improve sound quality should quantify the subjective evaluations of sound quality. Nor et al. developed a vehicle acoustical comfort index to define the acoustical comfortness of vehicles, and they established a link between comfort and psychoacoustic metrics [5]. They attempted to correlate the results of subjective evaluation of vehicle interior sound with measurable data such as loudness and roughness by using regression analysis. As a result of this study, they concluded that loudness mainly affects the comfort of vehicle interior sound. Wang proposed a sound quality model for synthesizing the annoyance of vehicle interior noises based on an artificial neural network (ANN) [6]. Wang showed that sound pressure level (SPL), loudness, sharpness and roughness are correlated to annoyance, and that the correlation coefficient between annoyance and loudness is extremely high, 0.923. Both these studies suggested that loudness mainly affects the vehicle interior sound quality. Lee [7] and Shin [8] focused on the booming sensation of vehicle interior sound during acceleration. They attempted to represent the degree of booming perception of vehicle interior sound. Lee developed the sound quality index of booming and rumbling sound by employing loudness with a middle

* Corresponding author.
E-mail address: yeonjune@snu.ac.kr (Y.J. Kang).

https://doi.org/10.1016/j.apacoust.2018.01.027
Received 6 August 2017; Received in revised form 17 December 2017; Accepted 30 January 2018

frequency component, sharpness, and roughness as the input data for an ANN model [7]. Shin proposed "booming strength" using pitch and loudness analyses to evaluate the booming perception of vehicle interior sound [8]. Both these studies focused on representing a common sensation, which is a booming and rumbling sensation. Moreover, Bisping focused on the pleasantness and powerfulness of vehicle interior sound, which are also common sensations [9]. Bisping observed a trade-off relationship between these two perceptual factors by using sound samples recorded under a second gear wide open throttle (WOT) driving condition. On the other hand, Kubo et al. concentrated on specific and complex feelings, i.e., "sportiness" and "luxurious impression" [10]. They considered two driving conditions (WOT acceleration and constant speed) and showed that subjects assess the sound differently for WOT acceleration and constant speed conditions. Based on factor analysis, they determined that sporty and luxurious impressions have different perception spaces of two and three dimensions respectively. They investigated sportiness by using 8 vehicles in WOT acceleration, and luxurious impression by using 7 vehicles at a constant speed. As a result, they expressed the sporty feeling of vehicle interior sound during acceleration as a linear regression between loudness and the slope between the frequency and time. Kwon et al. developed sporty sound quality index based on regression analysis [11]. They used sound samples recorded under the WOT driving condition and showed that loudness and sharpness are related to sportiness. However, roughness, which is highly related to rumbling perception [7], was not included in their sporty sound quality index. Wang stated that roughness caused by modulation was important to assess the vehicle interior sound quality because roughness was concerned with the perception of annoyance and powerfulness of sporty vehicles [12]. Therefore, roughness should be considered when developing a sporty sound quality index. Pflueger et al. indicated that roughness perception was extremely influenced by loudness when the degree of loudness differed significantly [13]. In other words, if researchers wish to pay attention to roughness, they must control loudness to the same degree. Therefore, it is necessary to investigate a model of sportiness that involves diverse psychoacoustic metrics, especially roughness, while excluding loudness in order to carefully consider the characteristics of vehicle interior sound.

In this study, a model of psychoacoustic sportiness was developed by using psychoacoustic metrics to build the specific and complex desired image, a "sporty" car. A jury test was carried out to collect subjective assessments of engine sound heard in a vehicle. Including roughness, a psychoacoustic metric which is commonly used in psychoacoustical studies [2,5,6,11,14–16] such as sharpness was also calculated. Moreover, the tonality-type metric has been revealed to have an impact on perceived sportiness [2]. Therefore, tonality was also calculated in this study. The loudness values of all the sound samples were adjusted to the same degree for excluding the effect of loudness.

2. Experimental methodology

2.1. Stimuli

The interior sounds of five vehicles (three vehicles with four-cylinder engines and two vehicles with six-cylinder engines) were recorded, and for the one car with four-cylinder engine, three types of mufflers in a direct suction manner were applied. As mentioned in the introduction, Bisping [9] and Kubo et al. [10] considered vehicle interior sound quality under the WOT acceleration condition. In particular, Kubo et al. considered two driving conditions (WOT acceleration and constant speed) and suggested that engine sounds should be evaluated differently for each driving condition. They investigated sportiness by using sounds recorded under WOT acceleration condition, whereas they used sounds recorded under constant speed condition to investigate the perception of a luxurious impression. Moreover, Kubo [17] stated that engine sound can be clearly perceived in acceleration. According to Kubo, the sporty impression is highly correlated with the

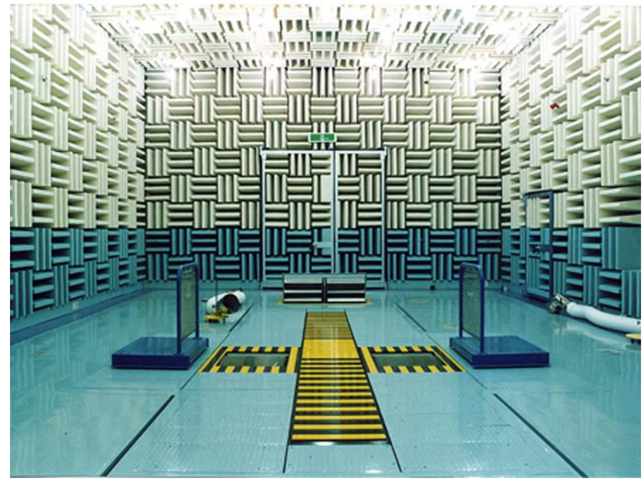

Fig. 1. Semi-anechoic room and dynamometer for sound recording.

evaluation of engine sound in the acceleration. In this study, we aimed to establish a model of psychoacoustic sportiness (i.e., the sporty impression). Therefore, recordings were obtained under the WOT acceleration condition from the start of acceleration in the second gear position to the maximum speed in the fourth gear position. To consider the binaural auditory system, an artificial head, HMS III of HEAD Acoustics, was used. Interior sound was obtained at a passenger seat in a semi-anechoic room with a dynamometer as shown in Fig. 1. Therefore, a total of seven stimuli were obtained.

Next, these samples were modified in order to obtain additional samples for a jury test, and sinusoidal amplitude modulation (SAM) was employed for the sample modification; accordingly, an envelope of a sound wave was formed at the modulation frequency. Modulation frequencies between 15 and 35 Hz are related to rumbling sound and the half-order of the engine revolution of vehicles [7]. Since rumbling sensation can contribute to sportiness, modulation at 30 Hz was applied to the recorded samples for emphasizing the rumbling sensation. Fig. 2 shows the demodulated and modulated sound waves. The abscissa is time and the ordinate is the real part of the sound pressure field (Pa). The bottom panel of Fig. 2 illustrates a modulated signal obtained by employing modulation on the signal shown in the upper panel of Fig. 2. It is evident that the signal in the bottom panel is significantly rougher

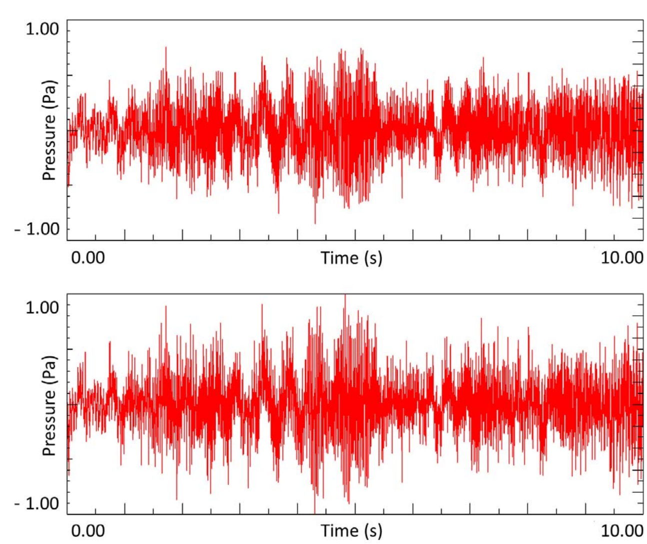

Fig. 2. Amplitude of sound waves with respect to time. The ordinate is the real part of pressure (Pa). The upper panel illustrates a demodulated sound wave and the bottom panel illustrates the modulated sound wave by applying modulation on the signal in the upper panel at the modulation frequency of 30 Hz.