ICIC Express Letters
Part B: Applications
Volume **11**, Number **6**, June **2020**

ICIC International ©2020 ISSN 2185-2766
pp. 545–549

LOW FREQUENCY DESIGN OF CAR INTERIOR SOUND USING DISTORTION PRODUCTS

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Received December 2019; accepted March 2020

Abstract. *When considering the acoustic design of automobiles, low-frequency sounds can increase the excitement levels of users. However, there are several problems involved when increasing the low-frequency levels of engine components. For example, it is difficult to balance silence and excitement if the different order component levels are increased. It is also difficult to generate heavy bass engine sounds in the cabin in practical scenarios. Thus, we consider an application of distortion products in the auditory system of the cochlea. Distortion products are perceived when two or more sounds with slightly different frequencies are played simultaneously. This study was conducted to examine the possibility of realizing powerful engine sounds using distortion products. As the first step for sound design, we investigated the relationship between combinations of complex sounds and pitch perception of distortion products. The results suggested the possibility of synthesizing a low-frequency component using distortion products inside a cochlea.*
Keywords: Distortion products, Pitch, Sound design

1. Introduction.

The sound environments within cars have been receiving considerable attention in recent years, as they can constitute a source of relief and enjoyment for drivers and passengers. Factors such as safety are essential in enabling people to drive automobiles with ease. However, catering to a driver's hobbies and personal preferences has also become increasingly important in adding value to the driving experience. In particular, a sense of excitement is desirable while driving a car. In previous studies, researchers have investigated the effects of the sound pressure levels of different order components of engine noise upon auditory impressions, via the semantic differential (SD) and factor analysis methods [1]. When the sound pressure level of the order component increases, the user's measured excitement factor tends to increase. It has been suggested that participants tend to feel excited when they hear an amplified low-frequency engine sound. However, this is difficult to implement, even if the goal is to design the engine sounds around the optimum sounds found from a model. It is possible to induce vibrations when low-frequency noises, such as booming noises, are boosted. Some researchers have adopted "missing fundamental" phenomenon in their sound designs [2]. When a complex

DOI: 10.24507/icicelb.11.06.545

tone consists of a number of harmonically related partials, the pitch corresponds to that of the "missing fundamental". This pitch is often referred to as the "pitch of the missing fundamental" [3]. However, very few previous studies have focused on distortion products for the sound design of engines. Therefore, we propose a method that does not involve the actual generation of low-frequency sounds. Instead, distortion products are adopted into the auditory system. In this paper, we first examine pitch perceptions of distortion products. Through psychological measurements, we clarify the relationship between the combinations of complex sounds and perceived distortion products. Then, the proposed method is applied to engine sounds.

2. **Distortion Products.** When listening to sounds composed of at least two sinusoidal tones, one can often hear extra tones at frequencies lower than those present in the sound. This is known as the cochlear nonlinear phenomenon [4], and it was observed about 50 years ago in the auditory nerve [5], in otoacoustic emissions [6], and on the basilar membrane [7,8]. The sounds most clearly perceived from stimuli composed of two tones correspond to the frequencies $2f_1 - f_2$, where $1 < f_2/f_1 < 2$. In this study, we focus on generating a frequency of 50 Hz, in consideration of its application to engine sounds. We calculated the kinetic energy of the basilar membrane (BM) [9] when $2f_1 - f_2 = 50$ Hz, which is perceived when $f_1 = 100$ Hz and $f_2 = 150$ Hz are presented at the same volume. As shown in Figure 1, distortion products of 50 Hz have an energy of about 35 dB, which is about 40 dB lower than the 75 dB measured for $f_1 = 100$ Hz. Therefore, it is necessary to decrease the 50 Hz frequency by approximately 30 dB to 40 dB to obtain energies similar to the $f_1 = 100$ Hz and $f_2 = 150$ Hz case when $f_1 = 50$ Hz and $f_2 = 100$ Hz. Even if the amplitude of $f_2 = 150$ Hz is reduced, the decrease in energy of the distortion product is small. Therefore, the amplitude of f_2 is decreased by 10 dB, 20 dB, and 30 dB. Thus, we conducted our experiment with six types of stimulus sounds (Table 1).

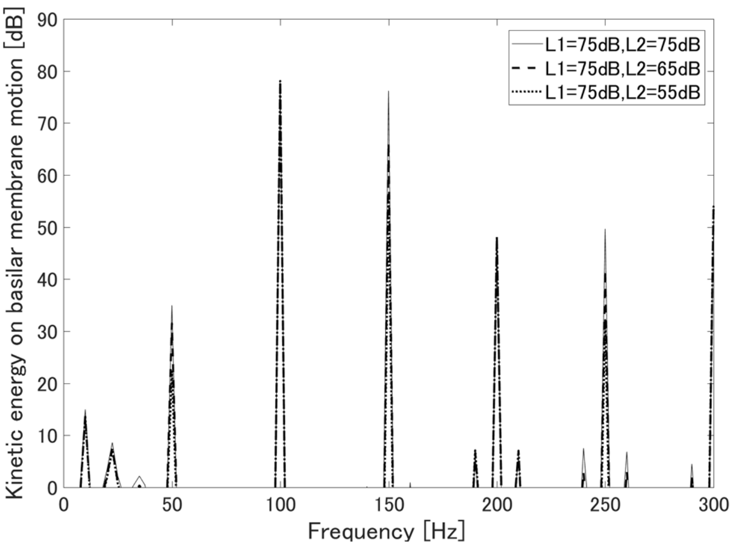

FIGURE 1. Calculated result of kinetic energy on basilar membrane (BM) motion ($f_1 = 100$ Hz and $f_2 = 150$ Hz)

3. **Methods: Auditory Impression Evaluation.** We compared the stimulus sound pitches listed in Table 1. The stimulus sounds were played for 5 s each.

3.1. **MUSHRA.** The participants compared the pitches of the six types of stimulus sounds using the "MUlti Stimulus test with Hidden Reference and Anchor (MUSHRA)" method [10]. The MUSHRA method has the advantage of being able to display several

Table 1. Stimulus sounds

Stimulus sounds	f_1 [Hz]	f_2 [Hz]
A	100 (75 dB)	
B	50 (45 dB)	100 (75 dB)
C	100 (75 dB)	150 (75 dB)
D	100 (75 dB)	150 (65 dB)
E	100 (75 dB)	150 (55 dB)
F	100 (75 dB)	150 (45 dB)

stimuli simultaneously, which enables participants to make direct comparisons. Following the rules in ITU-R BS.1534-3, one or more excerpts must be given a grade of 100, since the unprocessed reference signal is included as one of the excerpts to be graded. However, in accordance with a different point of the MUSHRA rules, the reference sound score was set here to 50 so as to more easily compare the pitches of the stimulus sounds. The reference tone was a pure tone of 100 Hz (stimulus sound A). When the pitches of the other stimulus sounds were perceived to be higher than that of the reference sound, they were scored higher than 50. In contrast, when the pitches of the other sounds were perceived to be lower than that of the reference sound, they were scored lower than 50.

3.2. **Participants.** A total of ten participants (between the age of 21-24 years; nine males, one female) with normal hearing abilities participated in the experiment. It is difficult for senior citizens with damaged outer hair cells to hear distortion products. Therefore, we selected participants in their twenties who have normal hearing capacities. Moreover, we did not consider driving experience as a factor, as this experiment is to confirm the pitch of the distortion products.

3.3. **Experimental environment.** The experiment was conducted in an anechoic chamber. Participants were seated in the chamber, which was maintained under comfortable thermal conditions. Figure 2 shows the schematic of the experimental environment in the anechoic chamber. We explained the experiment to the participants. Stimulus sounds were sent from the PC and played through a speaker (NUFORCE, S-1) and amplifier (NUFORCE, ICON-RJ45CX).

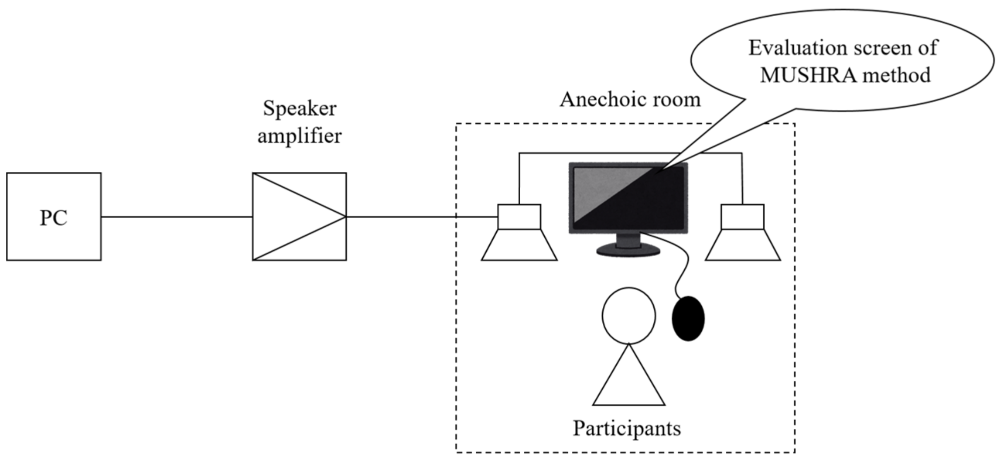

Figure 2. Schematic of the experimental environment

4. **Experimental Results.** Figure 3 shows a box plot of the evaluation results. We attempted to conduct a one-way analysis of variance (ANOVA) of the results. However, the Freidman test was then adopted because the data were not homoscedastic, and from

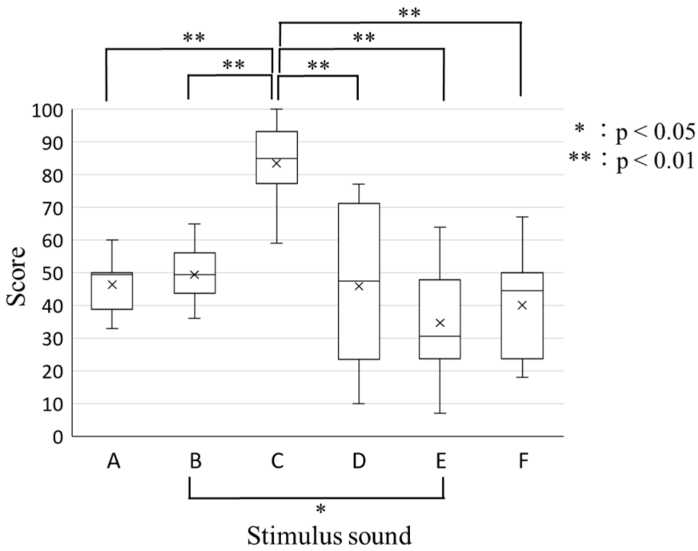

Figure 3. Experimental results

this test, the most significant effects were observed ($p < 0.01$). The differences in the perceived pitch of distortion products were found to depend upon the combination of complex sounds. Next, the Wilcoxon test was adopted to confirm the significant differences between each stimulus pair. Then, the scores of each participant were normalized, where the highest score was 100 and the lowest score was 0. Stimulus sound C – consisting of $f_1 = 100$ Hz and $f_2 = 150$ Hz at identical volumes – was perceived to have a higher pitch than the 100 Hz pure tone (stimulus sound A) and the 50 Hz stimulus sound B. In contrast, the results suggest that distortion products were perceived to have the lowest pitch when the $f_2 = 150$ Hz volume was decreased (stimulus sound E). Furthermore, we confirmed that there is a significant difference (of $p < 0.05$) between the stimulus sound B of 50 Hz and stimulus sound E of the distortion product.

5. **Conclusions.** In this study, we considered the application of distortion products as a method for creating perceptions of low-frequency sounds without actually generating the sounds themselves. We compared the pitches using the MUSHRA method, to clarify the relationship between combinations of complex tones and perceived distortion products. As a result, we confirmed that distortion products were felt to have the lowest frequency when the complex sound of $f_1 = 100$ Hz at 75 dB and $f_2 = 150$ Hz at 55 dB was played. The results suggest the possibility of synthesizing a low-frequency component using distortion products inside a cochlea. In future works, we will investigate whether it is possible to perceive distortion products for time-varying sounds, such as the sound of an accelerating engine. This method opens up new avenues of research for sound design.

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