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LOW-FREQUENCY SOUND DESIGN OF A CAR ENGINE USING DISTORTION PRODUCTS

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Abstract. *When considering the acoustic design of automobiles, low-frequency sounds can increase the excitement levels for users. However, there are several problems that accompany an increase in the low-frequency levels of an engine sound. For example, it is difficult to create a balance between silence and excitement when a sound's different order components are changed. It is also difficult to generate heavy bass engine sounds in practical scenarios. Thus, the application of distortion products in the auditory system of the cochlea is considered. 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 achieving powerful engine sounds using distortion products. At first, the relationship between different combinations of complex sounds and the pitch perception of distortion products was investigated. The results suggested the possibility of synthesizing a low-frequency component using distortion products inside a cochlea.*
Keywords: Distortion products, Pitch, Acceleration sound, Sound design

1. **Introduction.** Sound systems inside cars have been receiving considerable attention in recent years as they represent a source of relief and enjoyment for drivers and passengers. Factors such as safety are essential in enabling people to drive automobiles with ease. For example, the electric vehicle warning sounds are designed to alert pedestrians to the presence of electric vehicles (AVAS: Acoustic Vehicle Alerting System). This system yields some auditory impressions related to feelings [1]. Nevertheless, catering to a driver's hobbies and personal preferences is also becoming 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 applied the semantic differential and factor analysis method to investigating the effects of sound pressure levels of the different order components of an engine noise on the auditory impressions [2,3]. When the sound pressure level of an 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, designing such a low-frequency engine

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sound is difficult to implement, even if the goal is to design optimum engine sounds from a technical model. It is possible to induce vibrations when low-frequency noises, such as booming noises, are boosted. Some researchers have adopted a "missing fundamental" phenomenon in their sound designs [4]. When a complex 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" [5]. However, very few previous studies have focused on distortion products for the design of an engine's sound system. Therefore, we propose a method for designing an engine's sound system without actually generating low-frequency sounds. Instead, distortion products are incorporated into the auditory system. In this study, 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. The results suggested the possibility of achieving powerful engine sounds using distortion products. This rest of the paper consists of following five chapters: distortion products, methods and conclusions.

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 [6], and it was observed approximately 50 years ago in the auditory nerve [7], in otoacoustic emissions [8], and on the basilar membrane [9,10]. The sounds most clearly perceived from stimuli composed of two tones correspond to the frequencies $2f_1 - f_2$, where $1 < f_2/f_1 < 2$.

3. **Method 1: Auditory Impression Evaluation with Stationary Sounds.** In this method, the focus is on generating a frequency of 50 Hz, considering its application to the engine's sound. The kinetic energy of the basilar membrane [11] is calculated 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 approximately 35 dB, which is approximately 40 dB lower than the 75 dB measured for

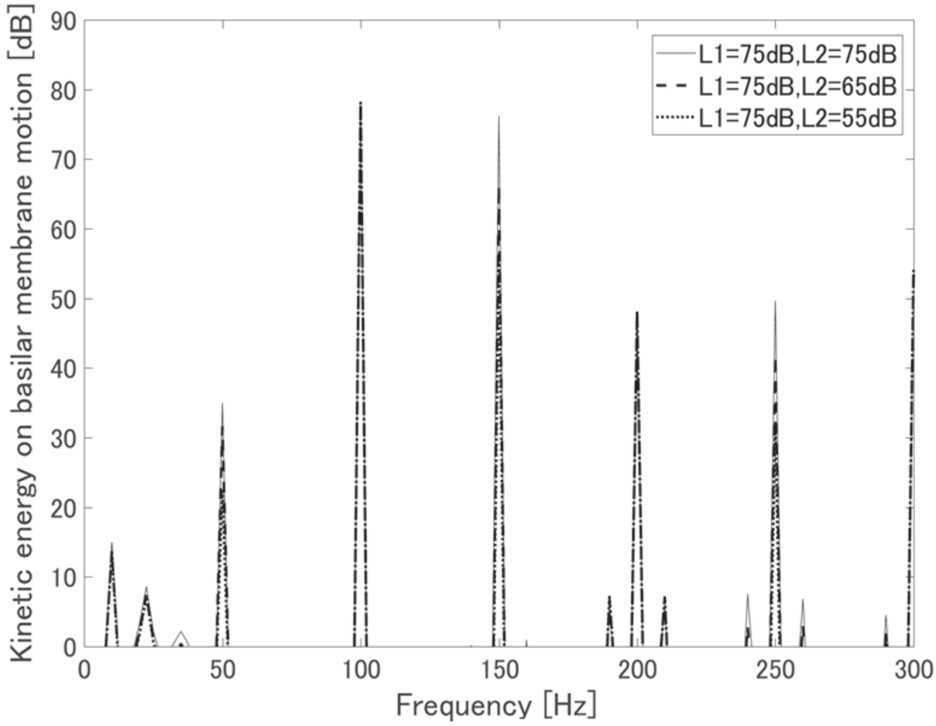

Figure 1. Calculated kinetic energy of the Basilar Membrane (BM) motion ($f_1 = 100$ Hz and $f_2 = 150$ Hz)

$f_1 = 100$ Hz (In Figure 1, the kinetic energy of f_1 is 80 dB according to the structure of the cochlear model). Therefore, it is necessary to decrease the energy of the 50 Hz frequency by approximately 30 dB to 40 dB to obtain energies similar to those of $f_1 = 100$ Hz and $f_2 = 150$ 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, an experiment with six types of stimulus sounds (Table 1) was conducted. The stimulus sound pitches are listed in Table 1. The stimulus sounds were played for 5 s each.

Table 1. Stimulus sounds used in Method 1

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)

3.1. **MUSHRA.** The participants compared the pitches of six different kinds of stimulus sounds using the "MUlti Stimulus test with Hidden Reference and Anchor (MUSHRA)" method [12]. Applying the MUSHRA method is beneficial as it can display several stimuli simultaneously, thereby enabling 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 as the unprocessed reference signal is included as one of the excerpts to be graded. However, in alignment with a different point in the MUSHRA rules, the reference sound score was set to 50 to compare the pitches of stimuli sounds more easily. 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 those of the reference sound, they were scored higher than 50. Conversely, when the pitches of the other sounds were perceived to be lower than those of the reference sound, they were scored lower than 50.

3.2. **Participants.** Ten participants (between the ages of 21 and 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, Participants in their 20s, who have normal hearing capacities, were selected. Moreover, driving experience was not considered to be a factor, as the aim of this experiment was 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, in which comfortable temperature conditions were maintained. Figure 2 presents a schematic of the experimental environment in the anechoic chamber. The experimental setup was explained to the participants fully. Stimulus sounds were sent from the PC and played through a speaker (NUFORCE, S-1) and amplifier (NUFORCE, ICON-RJ45CX).

3.4. **Experimental results.** Figure 3 presents a box plot of the evaluation results. We attempted to conduct a one-way analysis of variance of the results. However, the Freidman test was then performed because the data were not homoscedastic, and from this test, the most significant effects were observed ($p < 0.01$). The differences in the perceived pitch of distortion products were found to depend on different combinations of complex sounds. Next, the Wilcoxon test was performed to determine the statistically significant differences between each stimulus pair. Then, the scores of each participant were normalized, where

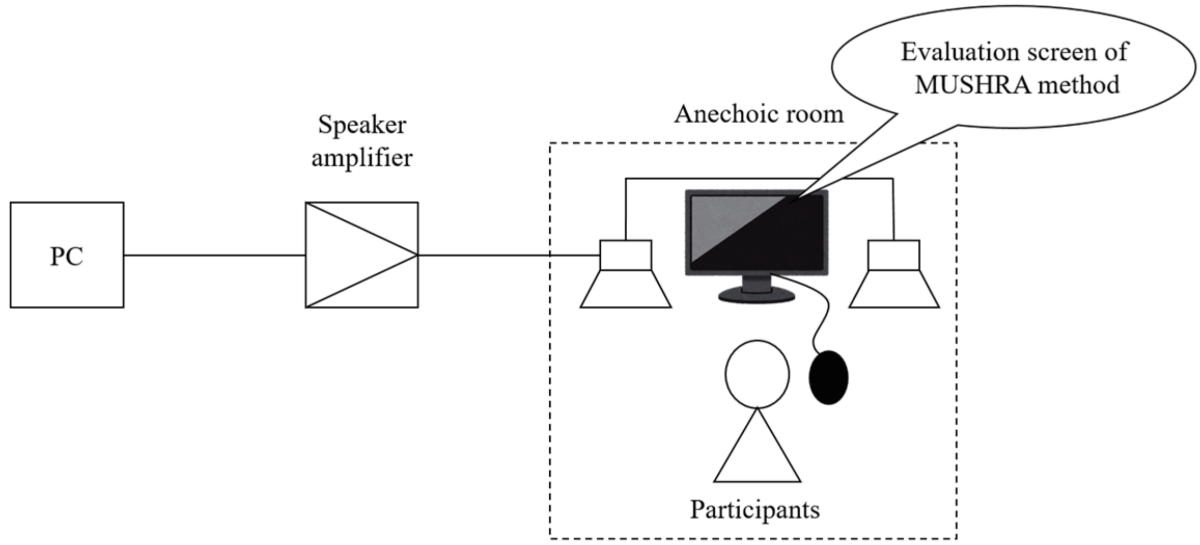

FIGURE 2. Schematic of the experimental environment

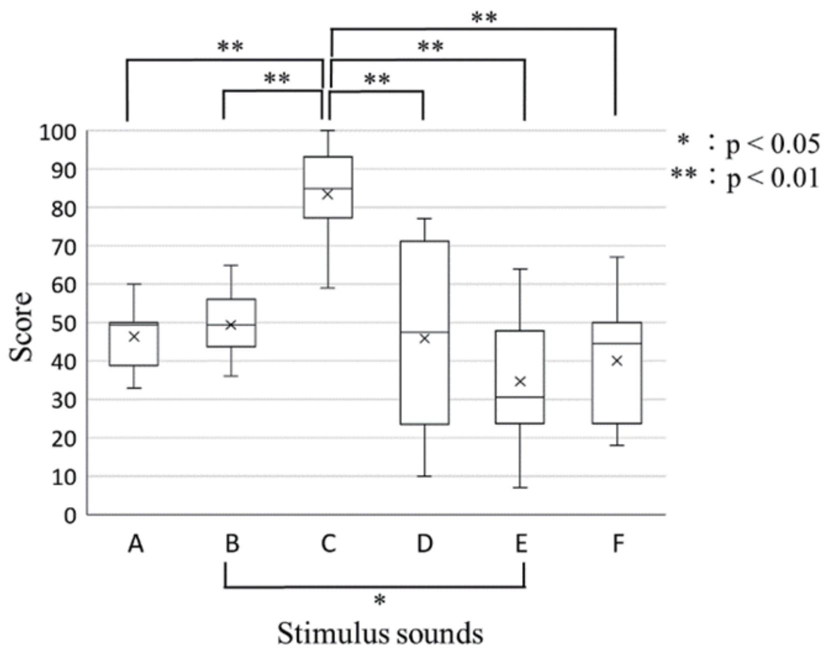

FIGURE 3. Experimental results of Method 1

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. By 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 statistically significant difference (of $p < 0.05$) between stimulus sound B of 50 Hz and stimulus sound E of the distortion product. The results suggest the possibility of synthesizing a low-frequency component using distortion products inside a cochlea.

4. Method 2: Auditory Impression Evaluation with Acceleration Sounds.

4.1. **Experimental outline.** In this method, the stimulus sounds are the chirp sounds generated when an in-line-4-cylinder engine revs up to between 1000 rpm and 4000 rpm.

Generating a frequency between 15 Hz and 60 Hz was focused on, taking into account how this frequency range applies to acceleration sounds. Thus, our experiment with six types of stimulus sounds (Table 2) was conducted. The stimulus sound pitches are listed in Table 2. The stimulus sounds were played for 6 s each. The participants, experimental environment and evaluation method are the same as those in Method 1.

Table 2. Stimulus sounds used in Method 2

Stimulus sounds	f_1 [Hz]	f_2 [Hz]
A	30 → 120 (75 dB)	
B	15 → 60 (45 dB)	30 → 120 (75 dB)
C	30 → 120 (75 dB)	45 → 180 (75 dB)
D	30 → 120 (75 dB)	45 → 180 (65 dB)
E	30 → 120 (75 dB)	45 → 180 (55 dB)
F	30 → 120 (75 dB)	45 → 180 (45 dB)

4.2. **Experimental results.** Figure 4 presents a box plot of the evaluation results. As in Method 1, the Friedman test and Wilcoxon test were performed to confirm the statistically 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. As a result, stimulus sound D, consisting of 10 dB lower $f_2 = 150$ Hz, was perceived to have the lowest pitch. In the model calculation, stimulus sound C had the highest power among the distortion products. However, there is a possibility that the sound was perceived higher than it really was. By contrast, stimulus sound D did not change the power of the distortion products considerably even when the level of f_2 was decreased by 10 dB. Therefore, these results suggest the possibility of distortion products displaying low auditory impressions depending on the presentation in the acceleration sounds.

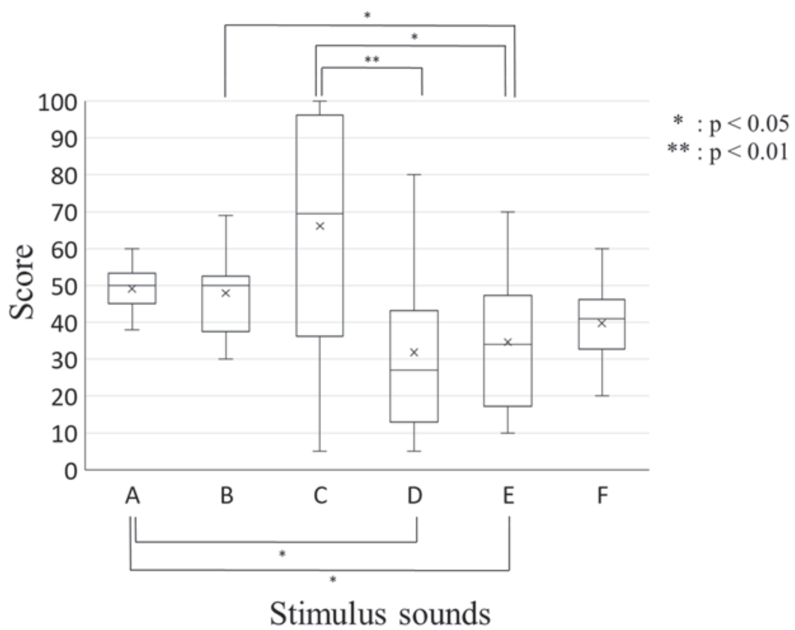

Figure 4. Experimental results of Method 2

5. Method 3: Auditory Impression Evaluation with Beginning Acceleration Sounds.

5.1. Experimental outline. In this method, to analyze the low-frequency sound at the beginning of acceleration, the first 2 s of the stimulus sounds were extracted. Moreover, stimulus sounds were shifted so that the distortion products were in the audible range, and generated in the a 20-35 Hz frequency range. Thus, an experiment with five types of stimulus sounds (Table 3) was conducted. The stimulus sound pitches are listed in Table 3. The stimulus sounds were played for 2 s each. The participants and experimental environment are the same as those in Method 1. In the MUSHRA of Method 2, because there were variations in the recognition degree of distortion products, the reference sound and the anchor were set at 100 points and 0 points respectively in Method 3.

Table 3. Stimulus sounds used in Method 3

Stimulus sounds	f_1 [Hz]	f_2 [Hz]
A	$60 \to 105$ (75 dB)	
B	$20 \to 35$ (75 dB)	
C	$40 \to 70$ (75 dB)	$60 \to 105$ (75 dB)
D	$40 \to 70$ (75 dB)	$60 \to 105$ (65 dB)
E	$40 \to 70$ (75 dB)	$60 \to 105$ (55 dB)

5.2. Experimental results. Figure 5 presents a box plot of the evaluation results. As in Method 1, the Friedman test and Wilcoxon test were performed to confirm the statistically significant differences between each stimulus pair. By setting f_2 as the reference sound and the anchor as $2f_1 - f_2$, it was easier to score participants, and there was less variation. As a result, stimulus sound C ($f_2 = 75$ dB) yielded the highest auditory impression among the distortion products. By contrast, stimulus sound D ($f_2 = 65$ dB) yielded the lowest auditory impression.

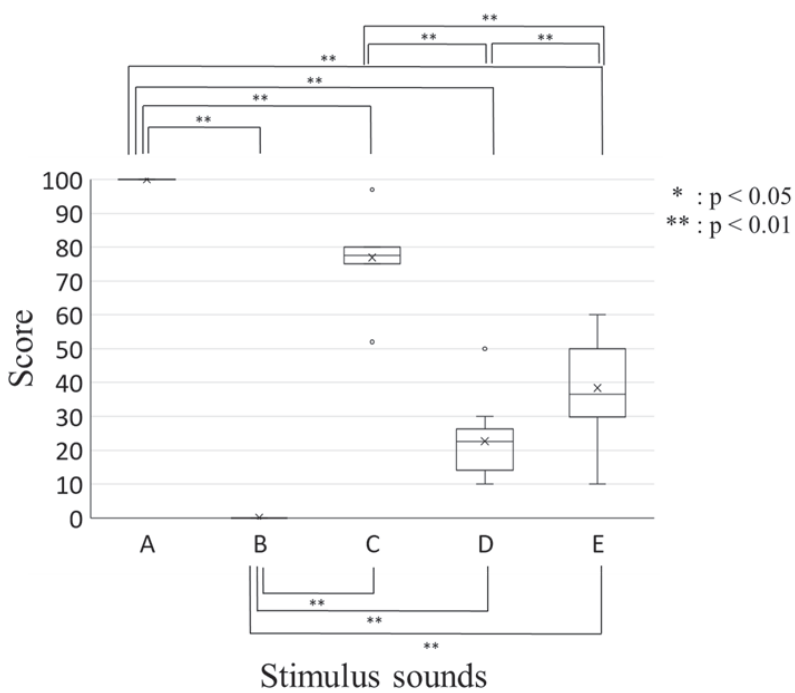

Figure 5. Experimental results of Method 3

6. **Conclusions.** In this study, we investigated the application of distortion products as a method for creating perceptions of low-frequency sounds without actually generating the sounds themselves. As a first step, we compared the pitches using the MUSHRA method to clarify the relationship between different combinations of complex tones and the perceived distortion products. As a second step, the application of distortion products to the acceleration sound, using a chirp sound close to the engine sound, was considered. As a result, it was confirmed that the participants felt that distortion products had the lowest frequency when the complex sound was played at frequency f_1 with an energy of 75 dB and at frequency f_2 with an energy of 65 dB. The results indicate 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 in noisy environment, such as roadway noise.

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