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# Sound design strategy for enhancing subjective preference of EV interior sound

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## ABSTRACT

In this study, sound design strategy for enhancing sound quality of EV interior noise is proposed and effectiveness of that is evaluated. In order to reduce annoyance of EV interior noise caused by its high frequency component, strategy of 'adding lower harmonics' was suggested. The strategy was expected to make sound more abundant and to decrease its sharpness. Following this strategy, 6 types of stimuli were composed by adding artificial sounds upon a recorded EV interior sound. Psychological experiments were conducted with 27 drivers using semantic differential method and 11-point numerical scale. Two of designed sounds were more preferred to original sound, and their sound characteristics were evaluated. A relationship between sound characteristics and subjective preference was examined.

Keywords: Sound design, Electric vehicle (EV), high frequency component

## 1. INTRODUCTION

In automobile industry, vehicle interior sound has become very important. Customers began to consider the sound as a significant factor when they make a decision of purchasing, so it sometimes determines whether the product succeeds or fails. So, efforts to improve indoor sound quality have been made in many automotive companies especially in engine sound design and its transmission.

Nowadays, electric vehicle (EV) has become a hot issue. From an acoustical point of view, the major sound sources of EVs are totally different from those of combustion engine vehicles, and so are characteristics of interior sounds. Without combustion, EVs provide fairly quiet and vibration-less circumstance to passengers. Otherwise, due to electric motor rotating very rapidly, EV sound contains high frequency components which are known to cause annoyance even when the level is quite low. Therefore, research on enhancing sound quality of EV interior sound should be constructed in order to meet the demands of potential customers.

In this paper, the method of adding artificial sound upon EV interior sound is considered. This approach does not need to modify structural design of vehicles, so it has a great advantage in terms of cost.

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## 2. Sound design strategy

### 2.1 Characteristics of EV sound

Interior sound of an electric vehicle in accelerating condition was recorded by 2-channel microphones inside torso. Total measurement time was about 15 seconds. The spectrogram of left-ear signal is shown in Figure 1.

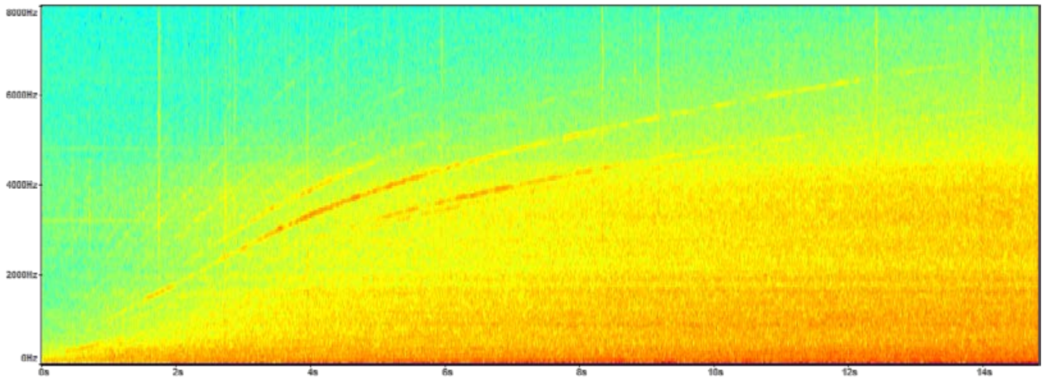


Figure 1 – Spectrogram of EV interior sound in accelerating condition

As shown in the figure, EV interior sound contains high frequency components which come up to almost 7kHz as RPM increases. The remarkable tone appears at 3 seconds and the frequency shifts from 3kHz to 4.5kHz until the level of it goes down. Spectral level of the component is fluctuating around 40dB in that period. In previous study, it was found out that this component is an annoying component and it makes subjects feel ‘sharp’ to the sound.

### 2.2 Sound design strategy – adding lower harmonics

The purpose of the research is to reduce the effect of the high frequency component by adding artificial extra sound so that preference of EV interior sound is improved. Because the extra sound is just added, total loudness of the sound would be essentially increased. And as well known, loudness negatively affects to preference of sound. Therefore, this loudness increment should be compensated with some way in order to reduce annoyance of the target sound. The only way to do is changing spectral characteristics of the sound in this study.

Firstly, one can easily think of masking the high frequency component by additional sound. According to Zwicker and Fastl, using broad band noise, the density level of masking noise should reach about 20dB below the component [1]. Also, using narrow-band/pure tone noise, center frequency of the masker sound should be located near that of target component, and the level should be even higher [2]. So, this way is not proper for the strategy in that it increases loudness of the sound too much or it makes the sound even sharper.

The second way is enhancing low frequency components to reduce sharpness of the sound. This can be done by various ways such as bass strengthening, adding low frequency tones or adding dull sound. With the fact that loudness increment should be minimized in mind, strategy of adding lower harmonics is suggested and evaluated in this study. By adding tones that have integer frequency ratio with the annoying component, three following effects can be expected. Sharpness of sound would decrease and the pitch of the tonal component would shift to the lowest frequency component. Also, sound would be more plentiful with harmonics.

## 3. Experiment

### 3.1 Stimuli

In order to use in a listening test, the recorded sound is slightly modified. Signal of 3s to 8s was extracted from the original sound, and some other components such as rattling noise were removed so that subjects could concentrate on the high frequency component.

Upon this baseline sound, following five types of sounds were designed. Figure 2 shows the adding components of each sound.

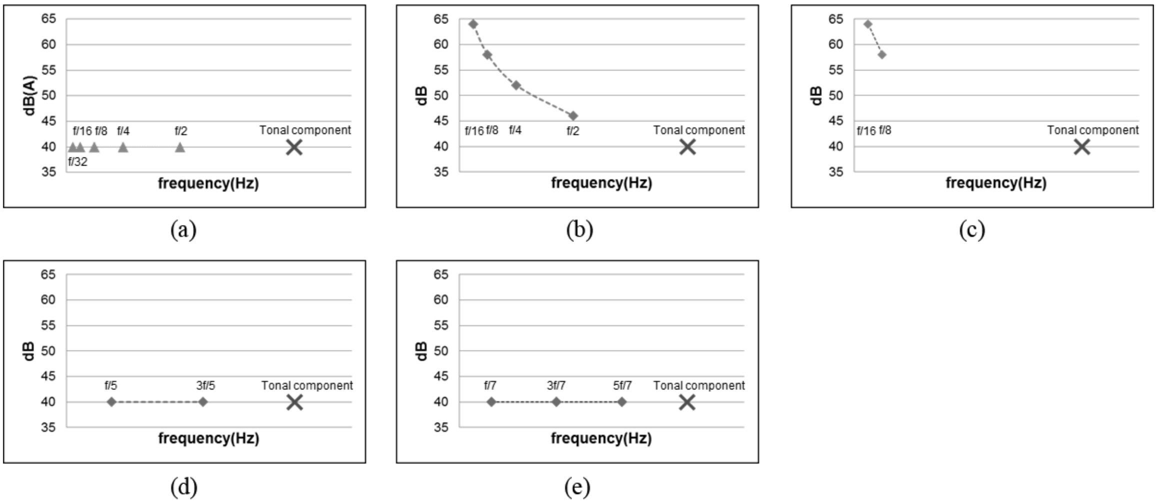


Figure 2 – Frequency components of additional sound for test stimuli

Sound 1 has 5 tonal components having octave interval as shown in Figure 2-(a). The level of all components are set to be 40dB(A). Sound 2 has 4 components also having octave interval, but energy distribution is set to be -6dB/octave. This decay rate copied spectrum of piano sound which usually has the rate of -12dB/octave [3]. In sound 3, 2 tonal components of sound 2 were omitted in order to reduce loudness increment. As shown in Figure 2-(d),(e), sound 4 and sound 5 have odd number harmonics : frequency ratio is 1:3:5 and 1:3:5:7 each. This idea was from closed-pipe instrument such as oboe and clarinet [3]. This type of instruments has only odd number harmonics of fundamental frequency, and its sound is known to be smooth. So, sound 4 and sound 5 were expected to make EV sound smoother.

## 3.2 Test environment

### 3.2.1 Subjects

Total 27 subjects (14 men and 13 women) were participated in the listening test. All participants had at least 1 year of driving experience.

### 3.2.2 Apparatus

The test was conducted in a half-frame of real car. Subjects evaluated sound sitting in the driving seat. Stimuli were played by headphone, and video of driving was reflected on the screen as shown in Figure 3.

Figure 3 – Listening test environment

### 3.2.3 Questionnaire

At first, rating scale was used to evaluate preference of each stimulus. This method is often used in listening tests because it does not need large number of sound pairs and has an advantage of statistical analysis [4]. 0 to 10 numerical method was used in this test.

Secondly, semantic differential evaluation was conducted with six adjective pairs. Used adjective pairs are pleasant/unpleasant, calm/dynamic, smooth/rough, loud/quiet, sharp/dull and luxury/cheap. Each adjective was evaluated in verbal scale composed of extremely, very, somewhat and neither.

Finally, subjects were asked to answer to several additional questions including important factor of sound in their preference.

### 3.3 Results

#### 3.3.1 Semantic differential evaluation

Because each adjective was evaluated in verbal scale, results were mapped into 0 to 6 numerical scale to be analyzed. Mean values of semantic differential evaluation are summarized in spring graphs in Figure 4.

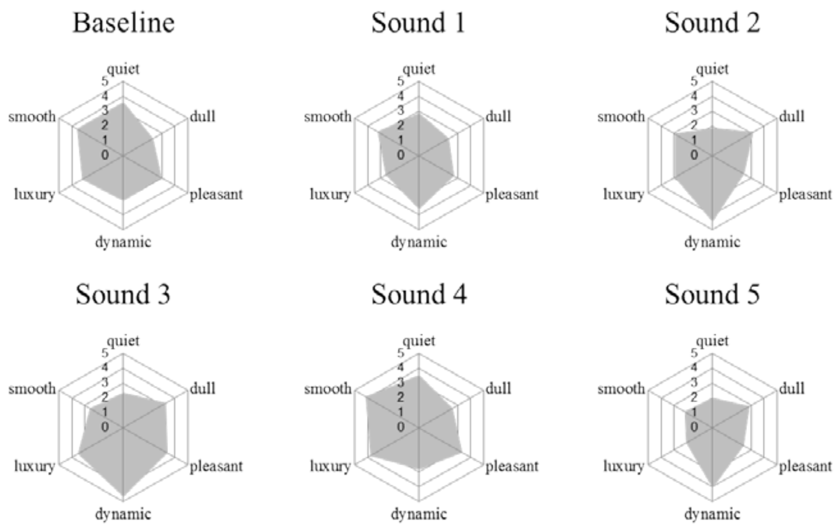


**Figure 4** – Subjective sound characteristics of each designed sound

In loud and quiet score, baseline is the quietest, which is natural because the level of it is the lowest. Sound 3 and Sound 4 have higher pleasant scores than baseline. This is a cheerful results in that some designed sounds are possibly more preferred than original sound. Subjects responded that Sound 3 was the least sharp among stimuli, and it was also on the top rank in dynamic score. Sound 4 has the highest score in luxury and smooth, but was the least dynamic.

#### 3.3.2 Preference

Table 1 shows the mean values and standard deviations of preference score. The result shows very similar tendency to that of pleasant score in semantic differential evaluation.

Table 1 – Mean values and standard deviations of preference score

| | Baseline | Sound 1 | Sound 2 | Sound 3 | Sound 4 | Sound 5 |
|---|---|---|---|---|---|---|
| Mean | 4.30 | 4.19 | 3.26 | 4.70 | 4.63 | 3.33 |
| Std | 1.9 | 2.3 | 2.6 | 2.3 | 2.1 | 2.0 |

Sound 3 and Sound 4 have again higher scores than baseline sound, so it is necessary to check their sound characteristics. In the previous part, those two sounds had distinct sound image. Especially, in ‘quiet’, ‘dull’, ‘dynamic’ and ‘smooth’ scores, statistically significant difference was found. Sound 3 is rough, dynamic, and not much sharp and Sound 4 is quiet, smooth and luxury.

With this clear division, it can be inferred that subjects can be divided into two groups. Some of them may prefer dynamic sound like Sound 3, while others prefer smooth and silent sound like Sound 4. Table 2 shows the result of correlation analysis between adjective ratings and preference scores. Group 1 contains those who prefer Sound 3 to Sound 4 and group 2 is those who prefer Sound 4 to Sound 3. There was no sexual or age difference between two groups.

Table 2 – Results of correlation analysis for each group

| Preference | Loud | Pleasant | Sharp | Dynamic | Luxury | Smooth |
|---|---|---|---|---|---|---|
| Group 1 | -0.34<br>$p<0.01$ | 0.60<br>$p<0.01$ | -0.31<br>$p<0.01$ | 0.33<br>$p<0.01$ | 0.28<br>$p=0.01$ | 0.04<br>X |
| Group 2 | -0.50<br>$p<0.01$ | 0.56<br>$p<0.01$ | -0.30<br>$p<0.01$ | -0.23<br>$p=0.03$ | 0.51<br>$p<0.01$ | 0.39<br>$p<0.01$ |

Interesting fact is that correlation direction of dynamic & preference is opposite. In group 1, dynamic score is positively correlated with preference, while group 2 shows negative correlation. This result is reasonable because characteristic of sound 3 is dynamic, and group 1 is who preferred this sound. Also, strong positive correlation between smooth and preference was found only in group 2.

### 3.4 Discussion

The main result of listening test is that EV sound is improved by the sound design strategy suggested in this paper. Sound 3 and Sound 4 were chosen in this test. Additionally, that passengers can be divided into two groups was found. Some people liked dynamic sound for car interior sound and others preferred smooth and quiet sound.

However, there are lots of things that are not covered yet. While Sound 4 had a good impression to subjects, Sound 5 got bad scores in many parts even though they come from the same idea. This means that characteristics of sound cannot be anticipated before the test yet. Large numbers of trial and error to apply this sound design strategy are still needed. Also, Sound 3 and Sound 4 may not be the best sound with this target sound. More studies are needed to understand how this design strategy works. Finally, what kind of facts made people have different preference still remains as questions.

## 4. Conclusions

In order to reduce the effect of high frequency component contained in EV interior sound, design strategy of ‘adding lower harmonics of tonal component’ was suggested. Several additional sounds with this strategy were designed and evaluated in the listening test.

Among stimuli used in the test, Sound 3 and Sound 4 had fairly good scores in semantic differential and preference ratings. Those two sounds satisfy two exclusive customer demands for sound so that they are preferred to original sound. Sound design strategy of Sound 4, which is adding 2 odd number harmonics, can be recommended for smoothing interior sound. That of Sound 3 may be applied to make sound more dynamic.


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