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Evaluation of independent sound zones in a car

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ABSTRACT

Recently sound field control techniques have been applied to vehicles that generate different sound zones in the inner space with loudspeaker arrays. A typical example in a car is to provide a driver and a passenger with different sound such as voice-guided navigation, music, or telephone voice. Acoustic contrast has been widely used as a performance index in sound field control that shows the difference between sound levels in the acoustically bright zone and the dark zone. However, these sound levels are usually measured with microphone arrays that are placed in the sound zones without the listeners. Thus these values can be different from what the listeners would have at their ears. This study compares the acoustic contrasts derived using microphone arrays with those using dummy head microphones at several positions and those using binaural microphones mounted in several subjects' ears. From this comparison, this study attempts to propose a simple and effective evaluation method of the independent sound zones.

Keywords: Sound field control, Independent sound zones, Acoustic contrast

1. INTRODUCTION

Sound zone control has been studied for recent decades that generates multiple independent listening zones with multiple loudspeakers. This technique focuses sound in a designated zone, and at the same time minimizes sound energy in other zones. The zone where sound energy is focused is called acoustically bright zone, and the zone where sound energy is minimized is called acoustically dark zone [1]. This control requires multiple loudspeakers, and thus car cabins are good places for the sound zone control because loudspeakers can be easily mounted on the headrest and on the surface of the car cabins. In addition, there is a desire for the driver and the passengers to have different audio contents. There have been a few studies that attempt the sound zone control in a car cabin [2-5]. In these studies, acoustic contrast has been used as a performance measure. This measure is defined as the ratio between acoustic potential energy in the bright zone and the dark zone [1].

However, this measure depends on the measurement setup such as the number and the positions of microphones. In fact different measurement setups were used in previous studies, and thus the contrast values in these studies cannot be directly compared. Moreover, these measurement setups did not take the effect of scattering by the users' head and torso into consideration, which has been known to be critical in the sound zone control at high frequencies [6]. Due to this effect, contrast that listeners would have at their ear positions could be significantly different from those values. The present study aims at investigating this difference. The ultimate objective of this project is to come up with an evaluation method that allows to compare the performances of sound zone control systems, and to provide a practical value for the acoustic contrast.

In the literature, Cheer and Elliott obtained 15-25 dB of acoustic contrast between the front seats and the rear seats. This contrast was measured with a linear array of 4 microphones for each seat [2,3]. Liao et. al. reported that 15 dB contrast was achieved, which was measured with a planar array of 15 microphones for each seat [4]. Choi showed that 30-40 dB or 20-30 dB of contrast was obtained depending on the setup of the bright and the dark zones below 1 kHz with 16 loudspeakers. A planar array of 30 microphones was used for each seat to measure the contrast [5]. However, there have been no studies to attempt to evaluate the acoustic contrast in a unified way to the best of the authors' knowledge. As a relevant measurement standard, ISO 5128 states measurement of noise inside a car, but this method is not appropriate for evaluating sound zone control systems as it uses only one microphone for each seat without considering the effect of the scattering [7].

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The present study compares three measurement setups. The first one is to measure sound pressure with a planar array of microphones. Most of previous studies employed a planar array, and thus this can be considered a conventional method. The second one is to measure sound pressure with the dummy head microphones at several positions. The third one is to measure at ear positions of several subjects with in-ear binaural microphones. The details of the measurement setup are shown in Section 2. Section 3 shows the measurement results, and Sections 4 and 5 discuss the results and conclude the study, respectively.

2. PROBLEM STATEMENT

2.1 Experimental setup: optimization filters and bright/dark zones

The experiments have been conducted in a smart sound laboratory at KAIST in South Korea. A midsize sedan (Hyundai Genesis EQ900) was used as shown in Fig. 1. In total 18 loudspeakers were installed in the car cabin including headrest loudspeakers. The driver seat was defined as the acoustically bright zone, and the rear right seat was defined as the dark zone.

Figure 1. Measurement with a planar array of microphones in a car cabin (by courtesy of Jung-Woo Choi)

Transfer functions between the loudspeaker input and the sound pressure at a planar array of microphones were obtained. The planar array is composed of 30 microphones (6 by 5). This array was placed in front of the headrest at the ear height in the driver seat (the bright zone) and the rear right seat (the dark zone). Figure 1 shows the measurement setup. If the sound pressure at the m-th microphone in the bright zone is denoted as $P(\vec{r}_{b,pl};\omega)$ where $\vec{r}_{b,pl}$ is the position of the microphone and ω is the angular frequency, the transfer function between the l-th loudspeaker and the m-th microphone in the bright zone can be denoted as $H^{(l)}(\vec{r}_{b,pl};\omega)$. Then $P(\vec{r}_{b,pl};\omega)$ and $H^{(l)}(\vec{r}_{b,pl};\omega)$ have the relation:

$$P(\vec{r}_{b,pl};\omega)=\sum_{l=1} H^{(l)}(\vec{r}_{b,pl};\omega)\,q^{(l)}(\omega), \tag{1}$$

where $q^{(l)}(\omega)$ is the filter for the l-th loudspeaker. For simplicity, ω is omitted in what follows. This equation can be expressed in a matrix form:

$$\mathbf{P}_{b,pl}=\mathbf{H}_{b,pl}\cdot\mathbf{q}\,. \tag{2}$$

In the same way, the pressure in the dark zone is expressed as

$$\mathbf{P}_{d,pl}=\mathbf{H}_{d,pl}\cdot\mathbf{q}\,. \tag{3}$$

Three optimization filter sets were obtained by the acoustic contrast control and provided by the smart sound laboratory at KAIST. Since the pure acoustic contrast maximization tends not to be robust, a regularization method with brightness constraints were applied [8]. This constraint prevents the acoustic brightness from decreasing below a certain threshold compared with the maximum brightness. In this work, the threshold values was set to be -1, -3, and -12 dB, respectively, and these filters are denoted as $\mathbf{q}_1$, $\mathbf{q}_3$, and $\mathbf{q}_{12}$. Three filter sets were used to investigate the effect of the optimization filter on the results. A filter with the lower threshold tends to provide the larger acoustic contrast, but it can be more sensitive to the effect of the scattering and experimental noise.

2.2 Measurement of acoustic contrast

To measure the acoustic contrast, white noise was filtered by the optimization filter sets, and sent to loudspeakers. Sound pressure levels were measured at microphones, and averaged in time domain. Then, these values were also spatially averaged.

2.2.1 Measurement with a planar array of microphones

The planar array that was used to obtain the transfer functions was employed again to obtain the acoustic contrast. Thus, the acoustic contrast values should be equal to what were predicted in the optimization. The microphone spacing was 4 cm. The acoustic contrast is obtained as

$$\alpha_{pl} = \frac{\overline{P}_{b,pl}^2}{\overline{P}_{d,pl}^2}, \tag{4}$$

where $\overline{P}_{b,pl}^2$ and $\overline{P}_{d,pl}^2$ are the spatially averaged sound pressure

$$\overline{P}_{b,pl}^2 = \frac{1}{M}\sum_{m=1}^{M}\left|P\left(\vec{r}_{b,pl}^{\,m}\right)\right|^2, \quad \overline{P}_{d,pl}^2 = \frac{1}{M}\sum_{m=1}^{M}\left|P\left(\vec{r}_{d,pl}^{\,m}\right)\right|^2. \tag{5}$$

2.2.2 Measurement with dummy head microphones

Measurement with binaural microphones for many listeners might be the ideal way of evaluating the sound zoning system. However, this method is not feasible in practice as it takes too much time and effort. The measurement with dummy head microphones can be an alternative method because it reflects the effect of scattering by the head and torso of a listener.

In this experiment, a dummy head microphone set (B&K HATS type 4128) was employed. The measurement was conducted at 12 positions in the bright zone, and 6 positions in the dark zone. In the bright zone, 12 positions are combination of front/center, high/low, and leaning 1/2/3. For front/center positions, the seat itself was moved by the automatic positioning. The center position is stored in the system, so that the seat can be placed in that position by pressing a button. The front position was 5 cm in front of the center position. For high/low and leaning 1/2/3, a zig that can fix the dummy head in a designated position was designed and constructed. In the low position, the ears of the dummy head is located about 2 cm lower than the headrest loudspeakers. The high position is 5 cm higher than the low one. The leaning 1 is defined as the position that the dummy head is contacted to the headrest. The inclination angle from the vertical axis was approximately 20 degrees. Leaning 2 and 3 are more upright, and the inclination angle was 18 degrees and 13.5 degrees, respectively. Figure 2 shows the leaning 1/2/3. During the measurement, another dummy head microphones were placed in the dark zone, but the signals measured with this microphones were not used in this study.

In the dark zone, sound pressure was measured at 6 positions of the dummy head microphones: high/low and leaning 1/2/3. The inclination angles were 25, 22.5, and 20 degrees, respectively. During the measurement, another dummy head was placed in the bright zone.

The sound pressure in the bright zone is denoted as $P\left(\vec{r}_{b,dh}^{\,m}\right)$, and that in the dark zone is $P\left(\vec{r}_{d,dh}^{\,m}\right)$. The number of the measurement is 24 in the bright zone (12 positions x left/right ear), and 12 in the dark zone (6 positions x left/right ears). The odd indices indicate the left ear signals, and the even indices are the right ear signals.

The acoustic contrast with the dummy head microphones is expressed as

$$\alpha_{dh} = \frac{\overline{P}_{b,dh}^2}{\overline{P}_{d,dh}^2} = \frac{\frac{1}{24}\sum_{m=1}^{24}\left|P\left(\vec{r}_{b,dh}^{\,m}\right)\right|^2}{\frac{1}{12}\sum_{m=1}^{12}\left|P\left(\vec{r}_{d,dh}^{\,m}\right)\right|^2}. \tag{6}$$

2.2.3 Measurement with binaural microphones

In order to obtain the sound pressure at ear positions of users, in-ear binaural microphones (B&K type 4101-B) were worn on the ears of 13 subjects. The subjects were asked to sit still during the measurements. They had two postures: standard posture and free posture. In the standard posture, the seat position was fixed, and they were asked to sit up straight and grab the handle. In the free posture, they were asked to choose the seat position and have comfortable postures for them. The ages of the

Figure 2. Positioning of the dummy head microphone (leaning 1/2/3)

subjects vary from 30 to 40. All subjects were male. The distance from the seat and the ears varies from 64.8 cm to 72.1 cm.

The sound pressure in the standard posture is denoted as $P_s\left(\vec{r}_{b,bi}\right)$, and that in the free posture is $P_f\left(\vec{r}_{b,bi}\right)$. For each posture, the number of the measurement points is 26 (13 subjects x left/right ears). The odd index corresponds to the left ear, and the even index to the right ear. For the dark zone, the sound pressure values measured with the dummy head microphones were used to obtain the acoustic contrast:

$$\alpha_{bi} = \frac{\overline{P}_{b,bi}^2}{\overline{P}_{d,dh}^2} = \frac{\frac{1}{52}\sum_{m=1}^{26}\left(\left|P_s\left(\vec{r}_{b,bi}\right)\right|^2 + \left|P_f\left(\vec{r}_{b,bi}\right)\right|^2\right)}{\frac{1}{12}\sum_{m=1}^{12}\left|P\left(\vec{r}_{d,dh}\right)\right|^2}. \tag{7}$$

3. Experimental results

3.1 Measured values of acoustic contrast

Figure 3 shows the acoustic contrast measured by the planar array, dummy head microphones, and binaural microphones (α_{pl}, α_{dh}, and α_{bi}) with three filter sets, $\mathbf{q}_1$ (top), $\mathbf{q}_3$ (middle), and $\mathbf{q}_{12}$ (bottom). In the top figure, all the contrast values are not as high as those with $\mathbf{q}_3$ and $\mathbf{q}_{12}$. The maximum value is lower than 30 dB, and most values are lower than 20 dB.

In the middle figure, mostly the acoustic contrast with the planar array is greater than those with other microphones. Especially, from 400 Hz to 1 kHz and above 10 kHz, the difference was larger, having a value of more than 20 dB at some frequencies. This shows that the acoustic contrast the listeners perceive can be significantly different from what is measured with a planar array. The bottom figure shows similar tendency to the middle figure except that the acoustic contrast with the planar array increases around 2 kHz. However those with the dummy head microphones and the binaural microphones do not have a big difference.

3.2 Sound levels in the bright zone

Since the acoustic contrast is the ratio between the sound levels in the bright and the dark zones, it does not show what happens in each zone. In order to observe more details, sound levels in the bright and the dark zone need to be investigated separately. In this section, sound levels in the bright zone are shown. Sound field in the dark zone is considered to be relatively robust to the scattering and the experimental noise because the sound level is low. Moreover, the same spatially averaged sound level measured with the dummy head microphones in the dark zone was used to obtain both α_{dh} and α_{bi}.

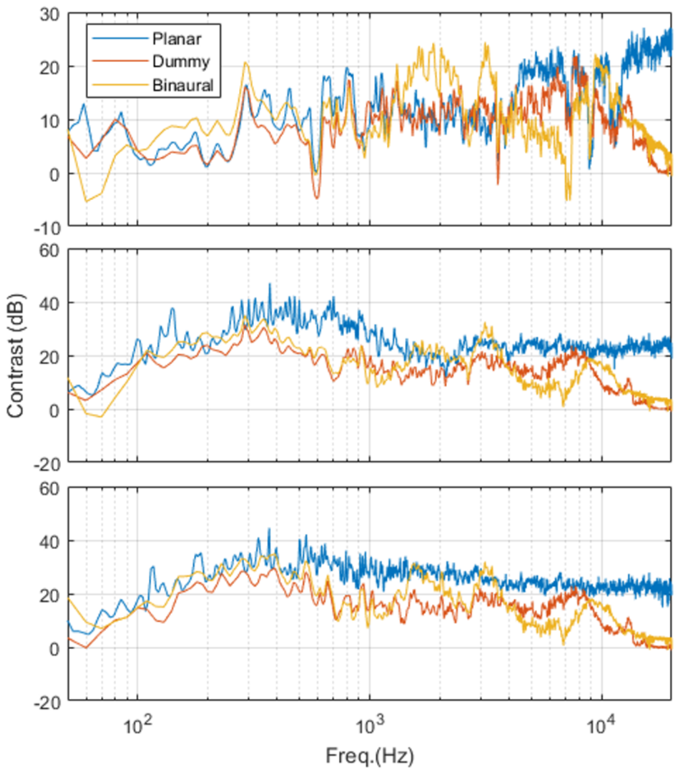

Figure 3. Acoustic contrast measured by the planar array, dummy head microphones, and binaural microphones with three filter sets (top: threshold 1 dB, middle: 3 dB, bottom: 12 dB).

3.2.1 Overall level

Figure 4 shows the overall level from 100 Hz to 10 kHz with the dummy head microphones at each position. Positions 1 to 6 are high positions in the height, and 7 to 12 are low positions. Positions 1, 2, 7, and 8 are leaning 1, positions 3, 4, 9, and 10 are leaning 2, and positions 5, 6, 11, and 12 are leaning 3. Odd numbers are center positions, and even numbers are front positions. Leaning 1 leads to the highest value. This can be due to either the distance between the ears and the headrest loudspeakers or the area measured by the planar array.

Although the contrast values with $\mathbf{q}_3$ and $\mathbf{q}_{12}$ do not have a big difference (Fig. 2), the sound levels in the bright zone have a considerable difference. Sound levels with $\mathbf{q}_3$ are greater than those with $\mathbf{q}_{12}$ at all positions.

Figure 5 shows the overall level from 100 Hz to 10 kHz with binaural microphones for all subjects. The level difference across the subjects is smaller than 3 dB with $\mathbf{q}_1$ and $\mathbf{q}_3$, whilst that with $\mathbf{q}_{12}$ is relatively large. The maximum difference is approximately 5 dB (between subject 3 and 6).

3.2.2 Levels in one third octave bands

Figure 6 (top) shows the sound levels in 1/3 octave bands with the dummy head microphones. It is clearly seen that the higher threshold leads to the lower levels in the bright zone. In addition, the higher threshold leads to the larger standard deviation as shown in Fig. 5 (bottom). This means that the sound field generated by the higher threshold is more sensitive to the scattering and the experimental noise.

The similar tendency can be observed in Fig. 6, which shows the sound levels and the standard deviations in 1/3 octave bands with the binaural microphones. The sound level with $\mathbf{q}_{12}$ has the lowest values and the largest standard deviation. At 300 Hz, the standard deviation has a large value in both Figs. 6 and 7. The wavelength at 300 Hz is about 1.1 m, so this can be due to the effect of the head and the torso.

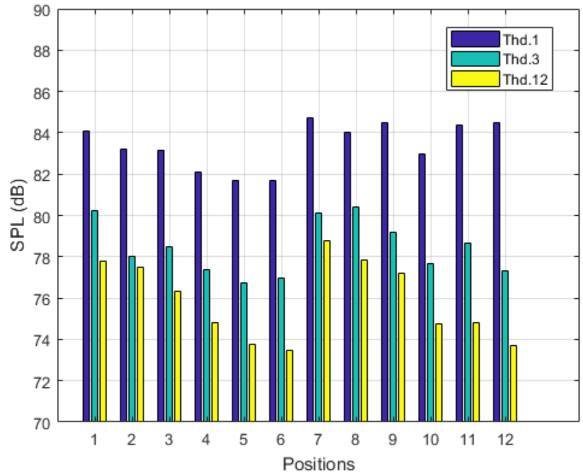

Figure 4. Overall level (100 Hz to 10 kHz) measured with the dummy head microphones in the bright zone

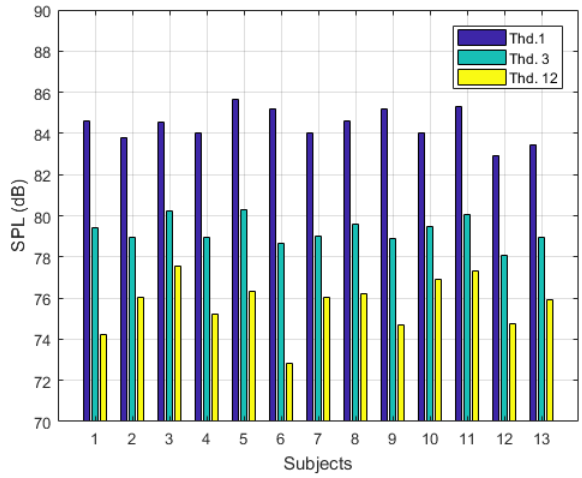

Figure 5. Overall level (100 Hz to 10 kHz) measured with the binaural microphones in the bright zone

In contrast, there are some differences between these figures. At 6300 Hz, the standard deviation has the largest value only in Fig. 7. This difference can be attributed to individual differences of head and torso that the dummy head microphones does not have. From 1 kHz to 4 kHz, the sound level in Fig.6 (top) has a fluctuation along the frequency, whilst that in Fig. 7 (top) has a relatively smooth curve. This might be related to the difference in the absorption of sound on the skin and the cloth of the subjects.

4. DISCUSSIONS

4.1 Estimation of 'listener acoustic contrast'

One of the ultimate goals of this work is to propose an evaluation method of the independent sound zone system that provides the similar results to the measurement with binaural microphones by using measurements with dummy head microphones. For example, the averaged squared sound pressure with binaural microphones $\overline{P}^2_{b,bi}$ could be expressed with the squared sound pressure with dummy head microphones $\left|P\left(\vec{r}_{b,dh}\right)\right|$.

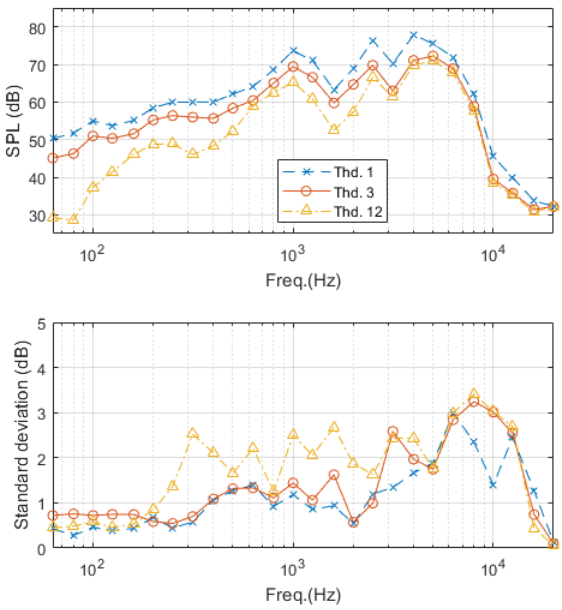

Figure 6. Sound levels (bottom) and standard deviation (bottom) in 1/3 octave bands with the dummy head microphones

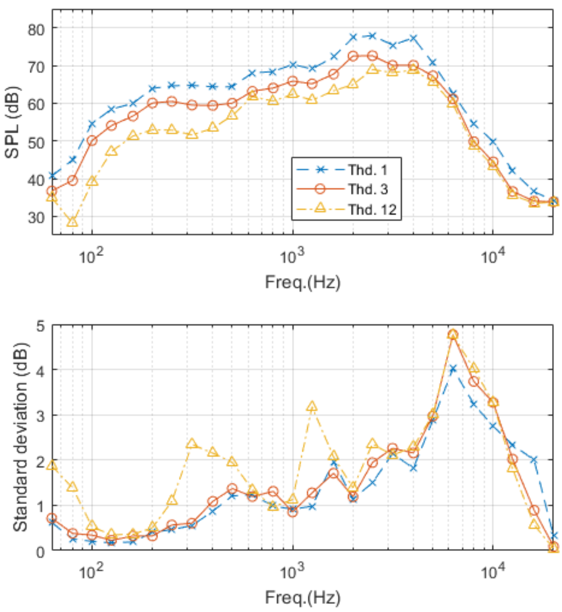

Figure 7. Sound levels (bottom) and standard deviation (bottom) in 1/3 octave bands with the binaural microphones

$$\overline{P}_{b,bi}^{2} \cong \sum_{m=1}^{M} \mu^{(m)} \cdot \left| P\left(\vec{r}_{b,dh}\right) \right| \quad , \tag{8}$$

where $\mu^{(m)}$ is the weight. To make this weight non-negative, non-negative least squares method can be applied [9].

4.2 Factors affecting the acoustic contrast

The sound pressure was measured at 12 positions with the dummy head microphones. Among the position changes, the inclination angle of the head and the torso was the most critical factor that affects the acoustic contrast. As shown in Fig. 3, the shorter is the distance between the ears and the headrest, the larger is the contrast value. On the contrary, the height of the ears and the position of the seat itself were not as critical as the inclination angle.

5. CONCLUSIONS

This study compares acoustic contrast values measured in different ways. The first method was to measure with a planar array of microphone, and take average of the sound pressure values. The second method was to measure with a dummy head microphone, and the other one was to measure with binaural microphones for several subjects.

Results show that the acoustic contrast with a planar array is considerably different from those with the other microphones. This implies that the acoustic contrast with a planar array is not enough to reflect the performance of the system. The acoustic contrast that listeners perceive can be significantly different.

Another finding is that the distance between the ears and the headrest is more critical than the other factors. Thus, in the measurement of the acoustic contrast, the inclination angle should be considered.

In addition, the noticeable differences between measurements with the binaural microphones and the dummy head microphones was found such as the fluctuation with the dummy head microphones from 1 kHz to 4 kHz and the high standard deviation with the binaural microphones at 6300 Hz. The reasons for these differences should be further investigated.

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