2pEAb10. Vertical sound image control using level differences between parametric speakers

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Even though horizontal sound images can be controlled using the level difference between two loudspeakers, vertical sound localization is difficult. In this paper, we propose a method of controlling a sound image with sound level differences between two parametric speakers that have superdirectivity. Our proposed system uses sounds that are reflected on a wall. In our experiments, two parametric speakers were arranged 56.6 and 226.0 cm high, respectively. The installation angle of both parametric speakers was changed. Examined angles were 0°, ±5°, and ±10° from the horizontal plane. We subjectively evaluated the vertical sound localization, and examined the answers by the Wilcoxon rank-sum test. We obtained good performances when the parametric speakers were arranged at angles of ±10°.
INTRODUCTION

Stereophonic sound can be enjoyed on a system using such advanced signal processing as a 5.1-ch surround system. However, such systems have a sound localization problem because it is difficult to localize a sound image above and below a user. There are many studies of the vertical sound localization[1, 2], including a method that uses the sound level difference between two loudspeakers located on the subject's median plane[3]. These previous researches show that vertical sound localization can be controlled using the sound level difference[4]. However, the perceived elevation is lower than the height of the upper-side loudspeaker in an echoic room.

We previously proposed a method that controls a sound image that uses the sound level difference among four superdirectivity loudspeakers[5]. This system uses reflected waves to control sound images. Using reflected waves reduced effects to sound localization by identifying loudspeaker's position and influences of the ultrasound exposure[6]. In our previous study, we controlled the horizontal sound localization, but controlling the vertical sound localization is difficult. In this paper, we propose and evaluate an improved method of controlling a vertical sound localization that uses the changes of the installation angles of parametric speakers.

EXPERIMENT

We examined sound localization performances with reflected waves generated by parametric speakers. A sound level difference between two parametric speakers is used to control a sound image.

Parametric Speaker

We used a parametric speaker (Nippon Ceramic, Parametric speaker AS050AW3PF1) with superdirectivity (Fig. 1). This parametric speaker has 50 ultrasonic transducers whose diameter is 10 mm on the substrate (90.0 × 87.5 mm). The frequency of the carrier wave is 40±2 kHz. Since its directivity is 12°, its irradiated area is 2l tan6°, where l is the distance from the parametric speaker. We used two parametric speakers in our experiments.

Experimental Condition

We conduct subjective tests to examine the sound localization performances when the installation angles of the parametric speakers were changed. The installation angles were 0°, 5°, and 10° (Fig. 2). The heights of the parametric speakers were not changed. We conducted subjective tests in a 14.00×7.93×2.70 m lecture room. Its reverberation time was 340 ms, and the background noise level was 38.6 dB(A). The experimental arrangement is shown in Fig. 3. We used reflected waves from a wall that was divided into 27 blocks (Fig. 4) that were numbered from the upper left to the lower right. Two parametric speakers, called RU and RD, were
arranged horizontally to radiate to the $6^{th}$ and $24^{th}$ blocks. The sound pressure levels of the test signals were $58.0 \pm 0.3$ dB(A) at 2.34 m from the wall where the subjects were seated. We adjusted the directions of the parametric speakers with a laser pointer. The subjects were presented test stimuli and answered perceived positions of a sound image in the 27 blocks. They could answer with more than one position. The subjects were seven males and one female from 19 to 24 years old. The test stimuli were played by an audio interface (MOTU, 828mk3) connected to PC (Panasonic, Let's note R9) by USB. The test stimuli were a white noise whose duration was 0.7 s, which included a 0.1 s fade-in/out. The sound level differences between both parametric speakers were $-\infty$, -9, -6, -3, 0, 3, 6, 9, and $\infty$ dB. The level difference was obtained by subtracting the sound level of the upper side from the lower side. The case of transducing only the upper side was represented as $\infty$, and the case of only the lower was $-\infty$. The test stimuli were randomly presented three times to each subject.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2}
\caption{Installation angles of parametric speakers from horizontal plane.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3}
\caption{Experimental arrangement: two parametric speakers located on subject's right.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4}
\caption{Wall partitions and numbering for answer sheets.}
\end{figure}
RESULTS

All the answers were grouped by elevations. For example, answers 1, 2, and 3 were grouped together because they have the same elevation. Answers located in the center and left row were 0.2 most of the answers located in the right row. The differences among the experimental conditions were examined by the Wilcoxon rank-sum test. The significant level was 5 %. A two-side test was conducted for the cases of -3, 0, 3 dB. Other conditions were tested by a one-side test.

Figures 5, 6, and 7 show that the vertical localization results. RD means $-\infty$ dB, and RU means $\infty$ dB. X-marks, circles, and triangles denote the averages of the answers. An asterisk shows a significant difference, and the bars are the standard deviation. A dashed horizontal line is the average height of the subject ears. As the sound level differences changed, the perceived elevations also changed. In the 0 dB conditions, the answers exceeded the average height of the subject ears and were located in the center. However, the variance of the answers was large. In the single channel condition, $-\infty$ and $\infty$, the answers located near the center because we conducted our experiments in an echoic room. Conditions with significant differences exist when the absolute value of the sound level difference was large. We obtained particularly remarkable results when we compared the 0° installation angle with the 10° installation angle. A change in the installation angle produces good vertical sound localizations even in an echoic room.

![Figure 5](image1.png)

**Figure 5:** Results of subjective tests. X-marks are averages of answers when installation angles of parametric speakers were 0°. Circles are 5°.

![Figure 6](image2.png)

**Figure 6:** Results of subjective tests. X-marks are averages of answers when installation angles of parametric speakers were 0°. Triangles are 10°.
CONCLUSIONS

We proposed and evaluated a method of controlling a vertical sound image using two parametric speakers with superdirectivity. Our proposed method used the sound level difference between parametric speakers. We subjectively evaluated the sound localization when the installation angles of the two parametric speakers were changed. Subjects heard sound signals that were reflected by a wall and answered perceived positions of the sound image. Results show that a change of the installation angles of the parametric speaker effectively controls the vertical sound image. Future work includes the evaluation of the difference of subject locations.

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Figure 7: Results of subjective tests. Circles are averages of answers when installation angles of parametric speakers were 5°. Triangles are 10°.