Three-dimensional spatial sound-image design based on separating emission with curved-type parametric loudspeaker

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Abstract

A parametric loudspeaker has a sharper directivity by utilizing an amplitude modulated wave which integrates the carrier and sideband waves (ultrasound), and can form a spatial narrow audible area. Moreover, it can design the three-dimensional (3-D) sound-image on a reflective object with the reflected sound. In this paper, we propose the design method of the 3-D spatial sound-image without the reflective object. We focus on the radiation characteristics of acoustic waves which are radially transmitted from a sound source. In the proposed method, we design the 3-D spatial sound-image by reproducing the radiation characteristics of the virtual sound source in the air. Specifically, we form a focal point of emitted sounds by utilizing multiple parametric loudspeakers arranged on arc, and design the virtual sound source on it. In this paper, we utilize the separating emission of the carrier and sideband waves to achieve the silent area from the parametric loudspeakers to the focal point. In the separating emission, the audible area is formed in the particular area where the carrier and sideband waves overlap. Therefore, the proposed method can design the spatial sound-image with the silent area from the parametric loudspeakers to the focal point. In addition, the formed audible area is too small because of too sharper directivity in the separating emission using the conventional parametric loudspeaker. Therefore, we utilize the curved-type parametric loudspeaker which has the curved surface arrangement of ultrasonic transducers and has a wider directivity. Finally, we evaluated the effectiveness of the proposed method. As a result of the evaluation experiment, we confirmed the proposed method is effective for the 3-D spatial sound-image design.

Keywords: Parametric loudspeaker, Sound-image, Virtual sound source, Separating emission, Curved-type parametric loudspeaker
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1 Introduction

In the field of virtual reality, the mixed reality (MR) system has recently been focused as a technology for experiencing the virtual world [1]. This system can provide a higher realistic sensation by utilizing the technologies which reproduce three-dimensional (3-D) sound fields. Therefore, we have previously proposed a system for reproducing 3-D sound fields using a parametric loudspeaker [2]. The parametric loudspeaker [3, 4] has the flat surface arrangement of ultrasonic transducers, and achieves a higher directivity by utilizing an ultrasound wave. It can form a spatial audible area called “audio spot” [5] in which a particular listener can obtain the sound information. Furthermore, “reflective audio spot” [2] can be formed by utilizing the reflected sound with the parametric loudspeaker. Listeners in the reflective audio spot can perceive the 3-D sound-image in the air without using the reflective object. However, it is difficult to design the 3-D sound-image on the reflective object. Hence, the previous system has difficulty to combine with the 3-D holographic technology. Accordingly, our goal is to design the 3-D spatial sound-image as shown in Fig. 1.

Previously, we have proposed the design method of the 3-D spatial sound-image with multiple parametric loudspeakers [6]. Generally, acoustic waves are radially transmitted from the real sound source. Listeners perceive the sound-image on the position of real sound source clue to reflected sounds and reverberations in the room. Therefore, the previous method designs the 3-D spatial sound-image by reproducing the radiation characteristics of the virtual sound source in the air. Specifically, this method forms a focal point of emitted sounds by utilizing multiple parametric loudspeakers arranged on arc, and designs the virtual sound source on it. In addition, this method utilizes the separating emission of an amplitude modulated (AM) wave [7] to achieve the silent area from the parametric loudspeakers to the focal point. The separating emission is defined as the method using the carrier and sideband waves which are separated from the AM wave. In the separating emission, the audio spot is formed in the particular area where the carrier and sideband waves overlap. Therefore, the previous method can design the 3-D spatial sound-image without the unwanted audio spot in front of the focal point. However, this method has a problem that the formed audio spot is too small because the flat-type parametric loudspeaker has too sharper directivity.

In this paper, we therefore attempt to expand the audio spot on the design of 3-D spatial sound-image. The range of the audio spot depends on the directivity of the parametric loudspeaker. The directivity is decided by the surface shape of the parametric loudspeaker. Thus, we propose the design method of the 3-D spatial sound-image with curved-type parametric loudspeakers. The curved-type parametric loudspeaker [8] has the curved surface arrangement of ultrasonic transducers. It can form a wider directivity compared with the flat-type parametric loudspeaker. Therefore, the proposed method can design the 3-D spatial sound-
image with larger audio spot. In this paper, we confirm the effectiveness of the proposed method with the curved-type parametric loudspeakers through an evaluation experiment.

2 Design of 3-D spatial sound-image based on separating emission with flat-type parametric loudspeakers

We have previously proposed the design method of the 3-D spatial sound-image with flat-type parametric loudspeakers [6]. Figures 2 and 3 show the flat-type parametric loudspeaker and the overview of the directivity with the flat-type parametric loudspeaker, respectively. Figures 4 and 5 show the top and sectional views of the previous method, respectively. In this method, multiple flat-type parametric loudspeakers are three-dimensionally arranged on arc as shown in Figs. 4 and 5. In Fig. 5, the parametric loudspeakers in upper and lower positions emit the sideband waves, and the parametric loudspeakers in middle positions emit the carrier waves. In this method, the sideband wave is divided into the higher and lower frequency sideband waves [7] to reduce the sound deterioration caused by the harmonic distortion. Then, these sideband waves are emitted from the parametric loudspeakers in upper and lower positions, respectively. The emitted carrier and sideband waves are focused on a particular point, and overlap beyond the focal point. The focused sound is designed as the virtual sound source, and it is radially
transmitted while reproducing the radiation characteristics of the real sound source including reflected sounds and reverberations in the room. Then, listeners in the audio spot can perceive the 3-D spatial sound-image on the focal point.

However, as shown in Fig. 5, this method has a problem that the formed audio spot is too small because the flat-type parametric loudspeaker has too sharper directivity as shown in Fig. 3.
Design of 3-D spatial sound-image based on separating emission with curved-type parametric loudspeakers

In the previous method, there is the problem that the formed audio spot is too small. To solve this problem, we propose the design method of the 3-D spatial sound-image with curved-type parametric loudspeakers.

Figures 6 and 7 show the curved-type parametric loudspeaker and the overview of the directivity with the curved-type parametric loudspeaker, respectively. The curved-type parametric loudspeaker [8] has the curved surface arrangement of ultrasonic transducers. It focuses the emitted wave on a particular point, and then it can form a wider directivity as shown in Fig. 7. A curvature of the curved-type parametric loudspeaker is determined by the radius $r_1$ of the arc. In Fig. 7, $h$ represents the chord length of the arc, $d$ represents the beam-width,
and $r_2$ represents the distance between the focal point A and the point D. The beam-width $d$ is calculated as follows:

$$d = h \frac{r_2}{r_1}$$  \hspace{1cm} (1)

Figure 9: Enlarged view of silent area in Fig. 8

From Eq. 1, the beam-width $d$ depends on the curvature $r_1$. Therefore, the curved-type parametric loudspeaker can also steer the directivity by changing its curvature $r_1$.

Figure 8 shows the sectional view of the proposed method with the curved-type parametric loudspeakers. In this method, we utilize the curved-type parametric loudspeakers for the sideband waves, and utilize the flat-type parametric loudspeakers for the carrier waves as shown in Fig. 8 to achieve the audio spot with higher sound pressure level (SPL) [9]. The emitted carrier and sideband waves are focused on a particular point as same as the previous method. Then, these waves widely overlap beyond the focal point because the sideband waves have a wider directivity by utilizing the curved-type parametric loudspeakers. As a result, the proposed method can design the 3-D spatial sound-image with larger audio spot.

Figure 9 shows the enlarged view of the silent area in Fig. 8. In Fig. 9, $d_{\text{flat}}$ and $d_{\text{curve}}$ represent the beam-widths of the flat-type and curved-type parametric loudspeakers on the focal point, respectively. $\theta$ represents the angle of the curved-type parametric loudspeakers, $l$ represents the distance between the flat-type and curved-type parametric loudspeakers, and $x_{\text{focus}}$ represents the distance between the flat-type parametric loudspeakers and the focal point, respectively. In order to expand the audio spot, $d_{\text{curve}}$ should be larger than $d_{\text{flat}}$. Therefore, the relationship between $d_{\text{flat}}$ and $d_{\text{curve}}$ is represented as follows:

$$d_{\text{flat}} < d_{\text{curve}}$$  \hspace{1cm} (2)

$d_{\text{curve}}$ is calculated as follows:
\[ d_{\text{curve}} = \frac{h x_{\text{focus}}}{\cos \theta \sqrt{r_1^2 - \left(\frac{h}{2}\right)^2}} - h \]  

(3)

From Eqs. 2 and 3, the upper limit of \( r_1 \) is represented as follows:

\[ r_1 < \sqrt{\left(\frac{h x_{\text{focus}}}{\cos \theta (d_{\text{flat}} + h)}\right)^2 + \left(\frac{h}{2}\right)^2} \]  

(4)

In addition, in the silent area, the area \( w \) where the carrier and sideband waves overlap should be as small as possible to reduce the unwanted audio spot. On the other hand, the focal point should be formed on the center of each beam-width to achieve the higher SPL on the focal point. Therefore, in this paper, we define the upper limit of \( w \) as follows:

\[ w < d_{\text{flat}} \]  

(5)

\( w \) is calculated as follows:

\[ w = \frac{h \left(\frac{x_{\text{focus}}}{\cos \theta} - \sqrt{r_1^2 - \left(\frac{h}{2}\right)^2}\right)}{2 \sin \theta \sqrt{r_1^2 - \left(\frac{h}{2}\right)^2} + h \cos \theta} \]  

(6)

From Eqs. 5 and 6, the lower limit of \( r_1 \) is represented as follows:

\[ \sqrt{\left(\frac{h(x_{\text{focus}} - d_{\text{flat}} \cos^2 \theta)}{\cos \theta (h + 2d_{\text{flat}} \sin \theta)}\right)^2 + \left(\frac{h}{2}\right)^2} < r_1 \]  

(7)

From Eqs. 4 and 7, the range of \( r_1 \) is represented as follows:

\[ \sqrt{\left(\frac{h(x_{\text{focus}} - d_{\text{flat}} \cos^2 \theta)}{\cos \theta (h + 2d_{\text{flat}} \sin \theta)}\right)^2 + \left(\frac{h}{2}\right)^2} < r_1 < \sqrt{\left(\frac{h x_{\text{focus}}}{\cos \theta (d_{\text{flat}} + h)}\right)^2 + \left(\frac{h}{2}\right)^2} \]  

(8)

4 Objective evaluation experiment

We carried out the objective evaluation experiment to confirm the effectiveness of the proposed method.

4.1 Experimental conditions in objective evaluation

Table 1 shows the experimental conditions. Table 2 shows the experimental equipment. Figure 10 shows the experimental arrangement of the parametric loudspeakers and the microphones. In this experiment, for investigating a range of the audio spot, we measured the distributions of the SPL of audible sound (0~5 kHz) at the microphone positions as shown in Fig.10.
previous method, the carrier wave was emitted from the flat-type parametric loudspeaker in middle position, and the sideband waves were emitted from the flat-type parametric loudspeakers in upper and lower positions as shown in Fig. 10 (a). On the other hand, in the proposed method, the carrier wave was emitted from the flat-type parametric loudspeaker in middle position, and the sideband waves were emitted from the curved-type parametric

<table>
<thead>
<tr>
<th>Environment</th>
<th>Conference room</th>
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<tbody>
<tr>
<td>Ambient noise level</td>
<td>31.0 dB</td>
</tr>
<tr>
<td>Reverberation time</td>
<td>650 ms</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>96 kHz</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>40 kHz</td>
</tr>
<tr>
<td>Sound source</td>
<td>Japanese sentence (female voice)</td>
</tr>
<tr>
<td>Curvature $r_1$ of curved-type parametric loudspeaker</td>
<td>25.0 cm</td>
</tr>
<tr>
<td>Chord length $h$ of of curved-type parametric loudspeaker</td>
<td>18.4 cm</td>
</tr>
</tbody>
</table>

Table 2: Experimental equipment in objective evaluation

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Model</th>
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<tbody>
<tr>
<td>Microphone</td>
<td>SONY, ECM-88B</td>
</tr>
<tr>
<td>Microphone amplifier</td>
<td>HEG, MACA-800A</td>
</tr>
<tr>
<td>A/D, D/A converter</td>
<td>RME, FIREFACE UFX</td>
</tr>
<tr>
<td>Power amplifier</td>
<td>YAMAHA, IPA 8200</td>
</tr>
</tbody>
</table>

(a) Previous method with flat-type parametric loudspeakers
(b) Proposed method with curved-type parametric loudspeakers

Figure 10: Experimental arrangement in objective evaluation experiment

Figure 11: Distributions of SPL in objective evaluation experiment

Table 3: Average SPL in silent and listening area

<table>
<thead>
<tr>
<th></th>
<th>SPL in silent area (x = 25 ~ 75 cm)</th>
<th>SPL in listening area (x = 100 ~ 200 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Previous method</td>
<td>61.8 dB</td>
<td>56.0 dB</td>
</tr>
<tr>
<td>Proposed method</td>
<td>59.8 dB</td>
<td>60.4 dB</td>
</tr>
</tbody>
</table>

loudspeakers in upper and lower positions as shown in Fig. 10 (b). The focal point was formed at \( x = 100 \) cm. The angle \( \theta \) of the parametric loudspeakers for sideband waves was 20.0 degrees, and the distance \( l \) between parametric loudspeakers was 36.5 cm, respectively. In addition, we expected that the beam-width \( d_{\text{flat}} \) of the flat-type parametric loudspeaker on the focal point is 55.0 cm. Therefore, the range of \( r_1 \) is represented using Eq. 8 as follows:
From Eq.9, in this experiment, we utilized the curved-type parametric loudspeakers \((r_1 = 25 \text{ cm})\).

In this experiment, it is desirable that the SPL is lower in the silent area \((x = 25 \sim 75 \text{ cm})\), and the SPL is higher in the listening area \((x = 100 \sim 200 \text{ cm})\).

4.2 Experimental results in objective evaluation

Figure 11 and Table 3 show the experimental results. Figure 11 shows the distributions of SPL. Horizontal axis represents the microphone positions from the flat-type parametric loudspeaker in middle position, and left vertical axis represents the SPL. Table 3 shows the average SPL in the silent area \((x = 25 \sim 75 \text{ cm})\) and the listening area \((x = 100 \sim 200 \text{ cm})\). From Fig. 11 and Table 3, the proposed method achieved the higher SPL in the listening area compared with the previous method. Therefore, we confirmed that the proposed method can form wider audio spot. However, in the proposed method, the average SPL in the silent area was as high as in the listening area. We considered this reason is because the carrier and sideband waves overlapped in the silent area.

5 Conclusions

The previous method with flat-type parametric loudspeakers has a problem that the designed audio spot is too small. For overcoming this problem, in this paper, we proposed the design method of the 3-D spatial sound-image with curved-type parametric loudspeakers. From the experimental results, we confirmed that the proposed method is effective for expanding the audio spot. In future, we intend to decrease the SPL in the silent area by studying the arrangement and curvature of curved-type parametric loudspeaker.

Acknowledgments

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References


