A design of reflective audio spot with parabolic reflector for sound pressure improvement on separating emission of carrier and sideband waves

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ABSTRACT

A parametric loudspeaker can represent the audible sound to a narrow spatial area because of its sharper directivity. However, even in the parametric loudspeaker, acoustic reflections and intercepts become noise. To solve this problem, we have already proposed the audio spot design method based on separating emission of the carrier and sideband waves using multiple parametric loudspeakers. However, the former method has had the problem that the audio spot has a low sound energy. In this paper, we therefore propose a new audio spot design method based on separating emission of the carrier and sideband waves using the parabolic reflectors to achieve a large sound energy on the audio spot. The proposed method achieves the audio spot design with the large sound energy by re-collecting the carrier and sideband waves passed through the audio spot using the parabolic reflectors. It is important for the proposed method to utilize the parabolic reflectors corresponding to the carrier and sideband waves. Thus, we investigate the suitable curvature of the parabolic reflectors. We carried out the evaluation experiment for measuring the spatial distribution of the demodulated audible sound energy. As a result of the evaluation experiment, we confirmed the effectiveness of the proposed method.

Keywords: Parabolic reflector, Parametric loudspeaker, Separating emission, Audio spot
I-INCE Classification of Subjects Number(s): 01.4

1. INTRODUCTION

An electrodynamic loudspeaker has been used for reproducing an audible sound. It which has a wider directivity can represent the audible sound to many listeners at the same time. However, the audible sound may become a noise to non-target-listeners. To solve this problem, a parametric loudspeaker with a sharper directivity(1) has been used. The parametric loudspeaker can represent the audible sound to a particular area called “audio spot” (2, 3) to utilize the ultrasound. The parametric loudspeaker emits an amplitude modulated (AM) wave designed by amplitude-modulating the carrier wave with the audible sound. The AM wave demodulates to the audible sound as the difference tone between the carrier and sideband waves. However, even in the parametric loudspeaker, acoustic reflections and intercepts become noise to non-target-listeners. Thus, we have proposed the audio spot design method based on separating emission of the carrier and sideband waves with multiple parametric loudspeakers(4). However, the previous method has had the problem that the audio spot has a low sound energy.

Therefore in this paper, we propose a new audio spot design method based on separating emission of the carrier and sideband waves using the parabolic reflectors. The proposed method achieves the audio spot design with a higher sound energy by re-collecting the carrier and sideband waves passed through the audio spot by using the parabolic reflectors. It is important for the proposed method to design the parabolic reflectors corresponding to the carrier and sideband waves. Thus, we investigate the suitable curvature of the parabolic reflectors for the proposed method. In addition, we propose the optimal parabolic reflector shape to improve the sound energy on the audio spot based on the formulation of the parabolic reflector shape and the focal area.

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2. THE CONVENTIONAL SEPARATING EMISSION METHOD

The parametric loudspeaker emits the ultrasonic AM wave which is modulated by an audible sound. The AM wave consists of the carrier and sideband waves. The audible sound emitted by the parametric loudspeaker is reproduced as the difference tone between the carrier and sideband waves. Thus, we have proposed the audio spot design method based on separating emission of the carrier and sideband waves using multiple parametric loudspeakers(4). Overview of the conventional method is shown by Fig. 1. In it, $P_{d1}(t)$ including of the carrier wave ($P_c(t)$) and sideband wave ($P_s(t)$) is shown as follows.

$$\begin{aligned} P_{d1}(t) &= P_c(t-\tau_{c1}) + P_s(t-\tau_{s1}) \\ &\approx v_A(t-\tau_{s1}), \end{aligned} \tag{1}$$

where τ_{c1} is the delay time until the carrier wave reaches center of the audio spot from the parametric loudspeaker, τ_{s1} is also the delay time for sideband waves. The delay time between the carrier and sideband waves may be able to be ignored because the carrier wave is a pure tone in higher frequency. Thus, the sound wave which is represented at the particular area compositing the carrier and sideband waves equals to the emitted AM wave. Thus, in the particular area, the demodulated audible sound wave is generated. In addition, both of the carrier and sideband waves are non-audible sound waves because they are ultrasonic. Therefore in the conventional method, we can design the audio spot in the particular area compositing the carrier and sideband waves. However, the conventional method has the problem that the audio spot has a low sound energy.

3. THE PROPOSED SEPARATING EMISSION METHOD WITH PARABOLIC REFLECTORS

As described in the previous section, the conventional method has the problem that the audio spot has a low sound energy. Although the parametric loudspeaker has the sharper directivity, the sound wave emitted by the parametric loudspeaker is transmitted with an emission angle of about 0.07π rad. Thus, it is important for improving the sound energy to collect the carrier and sideband waves to the audio spot using the parabolic reflectors. Therefore in this paper, we propose a new audio spot design method based on separating emission of the carrier and sideband waves using the parabolic reflectors. In the proposed method, the audio spot has a higher sound energy by re-collecting the carrier and sideband waves passed through the audio spot using the parabolic reflectors. Overview of the proposed method is shown by Fig. 2. The wave $P_{d1}(t)$ including of the direct carrier and sideband waves is shown by Eq. (1). Therefore in the particular area, the demodulated audible sound wave is generated.

The carrier and sideband waves passed through the audio spot are re-collected in the particular area. Thus in the particular area, $P_{d2}(t)$ including of the re-collected carrier and sideband waves is shown as follows.

$$\begin{aligned} P_{d2}(t) &= P_c(t-(\tau_{c1}+\tau_{c2})) + P_s(t-(\tau_{s1}+\tau_{s2})) \\ &\approx \alpha \cdot v_A(t-(\tau_{s1}+\tau_{s2})), \end{aligned} \tag{2}$$

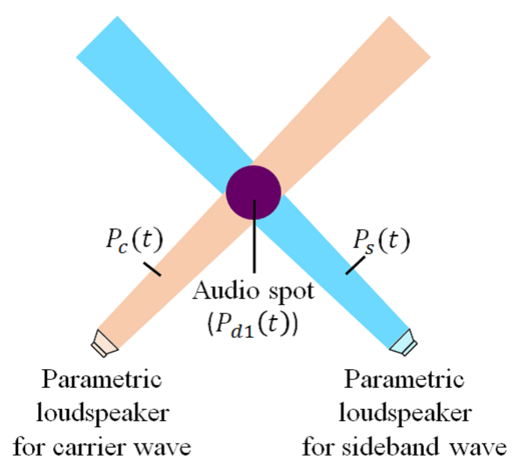


Figure 1 – Overview of the conventional method

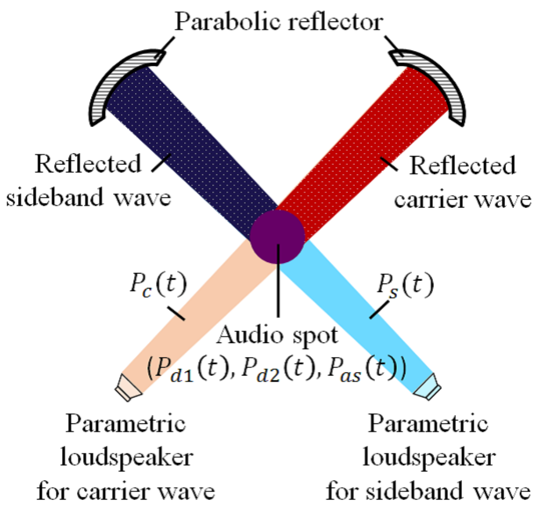


Figure 2 – Overview of the proposed method

where τ_{c2} is the delay time until the carrier wave reaches center of the audio spot from the parametric loudspeaker, τ_{s2} is also the delay time for sideband waves, $\alpha(\alpha < 1)$ is the coefficient including of distance attenuation, reflection coefficient and collection efficiency. The re-collected carrier and sideband waves demodulate to the audible sound in the particular area. In Fig. 2, $P_{d3}(t)$ is shown with using $P_{d1}(t)$ and $P_{d2}(t)$ as follows.

$$\begin{aligned} P_{d3}(t) &= P_{d1}(t-\tau_{s1}) + P_{d2}(t-(\tau_{s1}+\tau_{s2})) \\ &\approx v_A(t-\tau_{s1}) + \alpha \cdot v_A(t-(\tau_{s1}+\tau_{s2})). \end{aligned} \tag{3}$$

Thus, $P_{d3}(t)$ has the higher sound energy than $P_{d1}(t)$. In the proposed method, $P_{d3}(t)$ is distorted by the delay time ($\tau_{s1}+\tau_{s2}-\tau_{s1}=\tau_{s2}$).

3.1 Formulation of the optimal parabolic reflector shape

In the proposed method, it is important to collect the carrier and sideband waves emitted by the parametric loudspeaker to the audio-spot. Therefore, in this paper, we consider the optimal reflector shape for sound pressure improvement on the audio spot. Figure 3 shows diagram of the parametric loudspeaker, the parabolic reflector and the focal area. In Fig. 3, the origin O is center of the parabolic reflector, x-axis is the horizontal direction from the origin O, y-axis is the vertical direction from the origin O, d is the diameter of the parametric loudspeaker, l is the length between the parametric loudspeaker and the origin O. The position function of the parabolic reflector y is shown as follow.

$$y = \pm 2\sqrt{fx}, \tag{4}$$

where f is the focal length of the parabolic reflector. In Fig. 3, the sound wave ($\vec{SP}$) passes to point P from point S with a emission angle (θ) . P is the intersection of the sound wave ($\vec{SP}$) and the parabolic reflector. S is the upper edge of the parametric loudspeaker. ϕ is the incidence angle of the sound wave ($\vec{SP}$) to the parabolic reflector. The reflective wave ($\vec{PQ}$) passes to point Q from point P. The coordinates of points P and Q are shown as follows.

$$\begin{aligned} P(p_x,p_y): \quad p_x &= \frac{\tan\theta(l\tan\theta+\frac{d}{2})+2f-2\sqrt{f(\tan\theta(l\tan\theta+\frac{d}{2})+f)}}{\tan^2\theta}, \\ p_y &= (l-p_x)\tan\theta+\frac{d}{2}. \end{aligned} \tag{5}$$

$$Q(q_x,0): \quad q_x = p_x + \frac{p_y}{\tan(\theta+2\phi)}. \tag{6}$$

In Fig. 3, point F is the focal position of the parabolic reflector. Thus, all of waves emitted by the parametric loudspeaker are collected on between points F and Q. Therefore, when we design the audio spot between

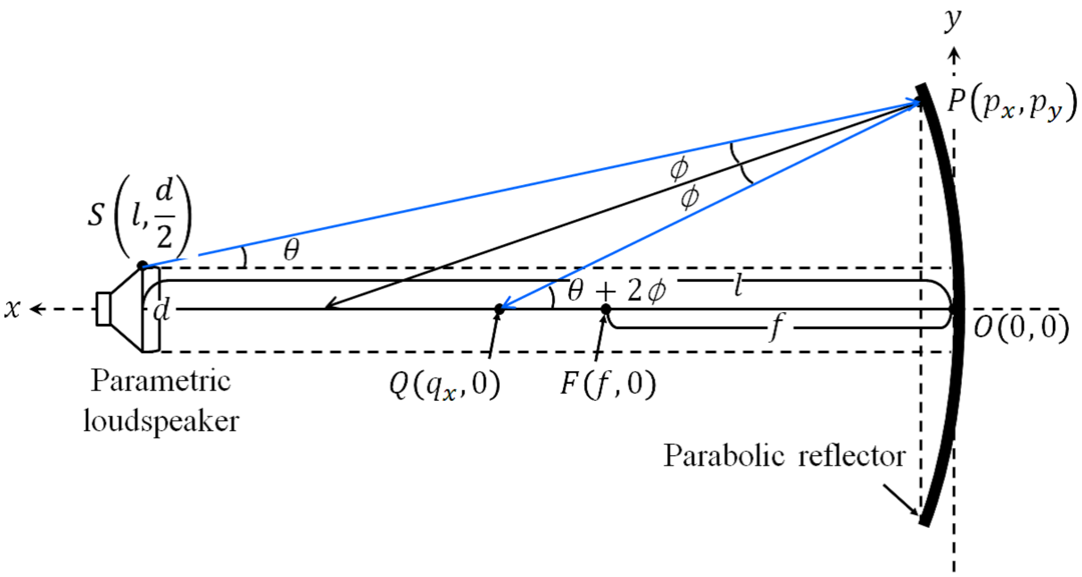


Figure 3 – Diagram of the parametric loudspeaker, the parabolic reflector shape and the focal area

points F and Q of the parabolic reflector, the reflector is the optimal shape for the sound pressure improvement on the audio spot.

4. EVALUATION EXPERIMENT

We carried out the evaluation experiment based on the formulation of the parabolic reflector shape. In this paper, we carried out the experiment with the parameters shown by Table 1.In the evaluation experiment, we used the parametric loudspeaker with the emission angle of 0.07 rad. However, there are non-reflective waves because the size of the parabolic reflector is small. Thus, we defined the emission angle in the evaluation experiment is the emission angle of the sound wave reflected on the edge of the parabolic reflector. Table 2 shows the coordinates of the points F and Q calculated in the parameters shown by Table 1. In the case using the parabolic reflectors with the focal length of 1.5 m, $\vec{FQ}$ includes the center of the measurement area. Therefore, the sound pressure level (SPL) of that case would be higher than the conventional method and the cases using other reflectors. In the evaluation experiment, we observed impulse responses measured with the time stretched pulse (TSP) method(5) in particular area (the audible sound area) compositing the carrier and sideband waves.

We evaluated the logarithm powers calculated from the direct and first reflection components of the impulse responses as the SPL. Figure 5 shows the experimental environments. We positioned the microphones at 25 locations in the 0.05m interval as shown in Fig. 5. Table 4 shows the experimental equipments. The parabolic reflector in the evaluation experiment is shown by Fig. 4. Table 3 shows the experimental condi-

Table 1 – The experimental parameters

Length between center of measurement area and the parabolic reflector	2.0 m
Length between the parametric loudspeaker and the parabolic reflector	3.0 m
Diameter of the parametric loudspeaker	0.19 m
Emission angle	0.02π rad
Focal lengths of the parabolic reflectors	1.0 m, 1.5 m and 2.0 m

Table 2 – Coordinates of points F and Q

Focal length	F	Q
1.0 m	(1.0, 0)	(1.3, 0)
1.5 m	(1.5, 0)	(2.3, 0)
2.0 m	(2.0, 0)	(3.7, 0)

Table 3 – The experimental conditions

Sampling frequency	192 kHz
Quantization	16 bits
Carrier frequency	40 kHz
Ambient noise(L_A)	34.1 dB
Sound source	TSP(2.4 sec)

Table 4 – Equipments of the evaluation experiment

Parametric loudspeaker	MITSUBISHI, MSP-50E
Power amplifier	VICTOR, PS-A2002
Microphone	SONY, ECM-88B
Microphone amplifier	Thinknet, MA-2016C
A/D, D/A converter	RME, Fireface UFX

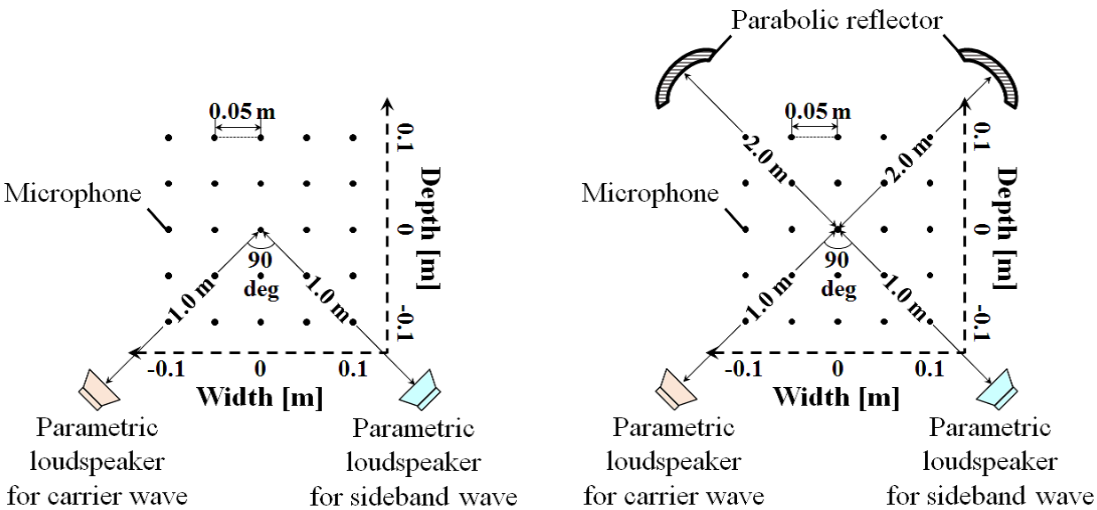
tions.

4.1 Results and considerations

Figure 6 shows the sound pressure level distributions of observed impulse responses on the conventional method and the proposed method. The distributions show the results normalized the SPL as 0 dB at the center of the measurement area of the conventional method. In the distributions, the red shows the high SPL, the blue shows the low one. Figure 6(c) shows that the SPL of the case using the parabolic reflectors with the focal length of 1.5 m is higher than the SPLs of other cases . Figure 6(d) shows that the amount of sound pressure improvement between point *F* and point *Q* is higher than other areas. These results show that reflective waves from the parabolic reflectors are collected on between point *F* and point *Q*.

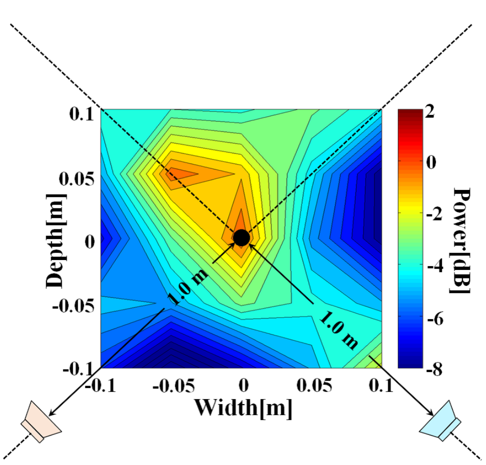
In addition, Fig. 7 shows the difference of logarithmic power which is the average of the measuring

Figure 4 – The parabolic reflector in evaluation experiment

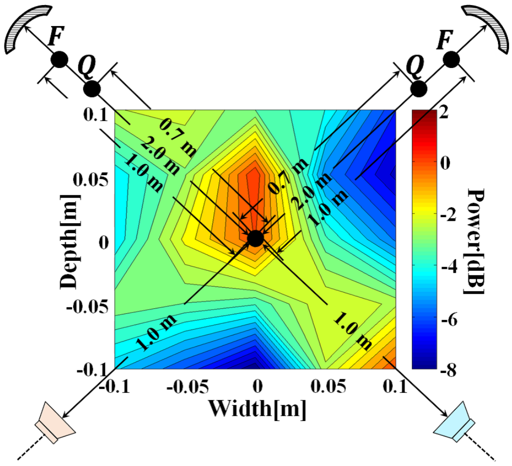


(a) The conventional method (b) The proposed method

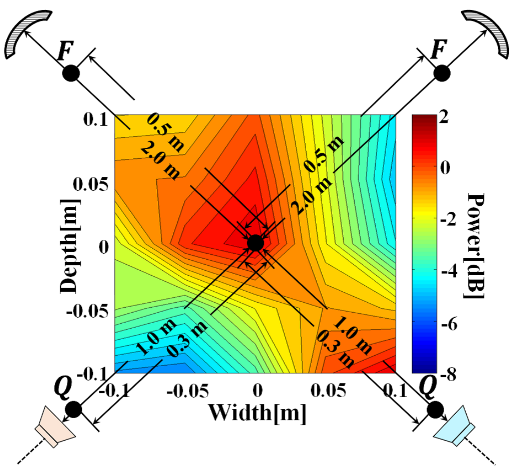
Figure 5 – Experimental environments



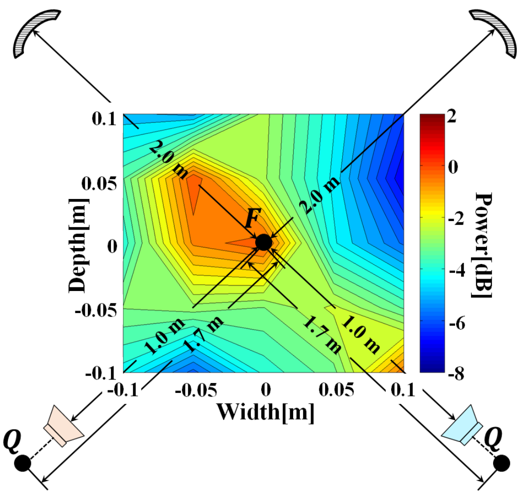
(a) The conventional method



(b) The proposed method (focal length: 1.0 m)



(c) The proposed method (focal length: 1.5 m)



(d) The proposed method (focal length: 2.0 m)

Figure 6 – The sound pressure level distributions of observed impulse responses

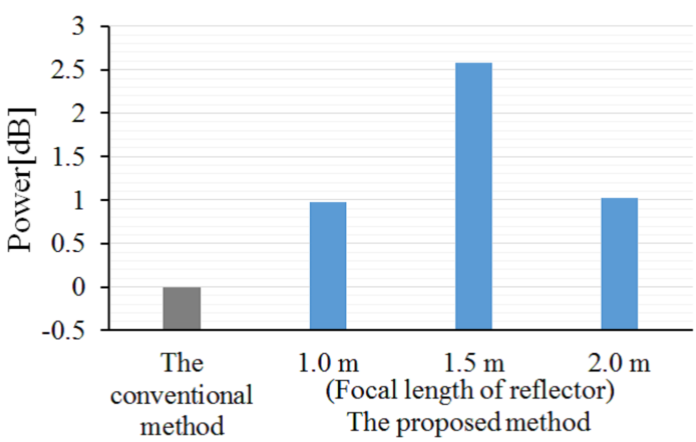


Figure 7 – The difference of logarithm powers calculated from observed impulse responses between the conventional method and the proposed method

area between the conventional method and the proposed method. It shows that the SPL of the case using the parabolic reflectors with the focal length of 1.5 m is improved 2.58 dB. In the case using the parabolic reflectors with focal length of 1.0 m, the amount of sound pressure improvement is lower than other cases because the measurement area is located on outside between points F and Q.

First, we confirmed that the SPL in the audible sound area is improved with the parabolic reflectors. Second, we confirmed the effectiveness of the parabolic reflector with the proposed optimal shape for improving the sound energy on the audible sound area. In this paper, we used the parabolic reflectors designed for improving the sound energy on only the intersection point of each $\vec{FQ}$. We presume that the sound energy on the audio spot is much improved to using the parabolic reflectors designed for improving on the overall audio spot.

5. CONCLUSION

In this paper, we propose a new audio spot design method based on separating emission of the carrier and sideband waves using the parabolic reflectors to achieve a high sound energy on the audio spot. Thus, we propose the optimal parabolic reflector shape to improve audio spot energy based on the formulation of the parabolic reflector shape. We carried out the evaluation experiment for measuring the spatial distribution of the demodulated audible sound energy. As a result of the evaluation experiment, we confirmed the effectiveness of the proposed method. In future work, we intend to formulate the optimal reflector shape based on the overlapped area of the sound waves emitted by multiple parametric loudspeakers to improve moreover the sound energy on the audio spot.

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