Proceedings of 20th International Congress on Acoustics, ICA 2010

23-27 August 2010, Sydney, Australia

The Steering for Distance Perception with Reflective Audio Spot

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PACS: 43.25.LJ

ABSTRACT

Parametric loudspeaker with higher directivity characteristic has been proposed. Parametric loudspeaker which utilizes ultrasound can form “audio spot” and can emit acoustic sound to a particular area. Recently, they have focused on “reflective audio spot” which is formed by the reflection signal with a parametric loudspeaker. The listeners can localize acoustic sound image on the reflector. If we can freely control the acoustic sound image, “reflective audio spot” should generally diffuse. To cope with this problem, we propose steering method based on the acoustic sound image control for distance perception with reflective audio spot. MINT (Multi input/output INverce Theorem) is utilized to design focal and null points with parametric loudspeaker array. In this paper, we firstly try to control acoustic sound image with three focal and null points which are located between the reflector and the listener. We thus design adaptive filters based on MINT for parametric loudspeakers. The proposed method should adaptively select the optimum filters based on the sound image distance. As results of objective evaluation, we confirmed that three focal and null points are designed with the proposed system. In addition, as results of subjective evaluation, we also confirmed that the subjects in 150 cm distance from reflector can perceive the distance difference on each designed acoustic sound images. However no subjects in 225 cm distance from reflector could clearly perceive that one. Thus in the future, we will try to form the focal point, sound pressure level of which increases more rapidly on focal point for superior steering method for the distance perception with more parametric loudspeakers.

INTRODUCTION

Acoustic sound which is emitted with a conventional loudspeaker should widely spread and be transmitted to the listeners. Thus, it may be also transmitted to undesired area for non-listeners. The non-listeners in undesired area may perceive non-required sound as noise. On the other hand, the simultaneous emission of different acoustic sounds with multiple loudspeakers may be perceived as noise even the listeners. To overcome these problems, parametric loudspeaker with the higher directivity characteristic is proposed.

Parametric loudspeaker is one of higher directivity loudspeaker systems [1],[2] that can only emit acoustic sound to a particular area. Parametric loudspeaker which utilizes ultrasound can form “audio spot”. Parametric loudspeaker has already been practically utilized for announcement in places such as museums and stations. Recently, they have focused on “reflective audio spot” which is formed by reflection signal with parametric loudspeaker. The listeners can localize acoustic sound image on the reflector. The reflective audio spot with parametric loudspeaker enables such new usage of loudspeaker system.

This paper focuses on the acoustic sound image on the reflector. If we can freely control the acoustic sound image, “reflective audio spot” should generally diffuse. To cope with this problem, we propose steering system based on the acoustic sound image control for the distance perception with the reflective audio spot.

CONVENTIONAL METHODS

Parametric loudspeaker

Higher directivity characteristic resides in ultrasound wave. Parametric loudspeaker utilizes the ultrasound wave as carrier wave. And amplitude of the ultrasound wave is modulated by audible sound wave. Frequency of the carrier wave, adjacent lower sideband (LSB) and upper sideband (USB) frequencies reside in the modulated ultrasound wave. Parametric loudspeaker emits intense amplitude the modulated ultrasound wave as primary wave. Then the secondary wave, such as difference tone or combination tone, is generated because of nonlinear interaction. The difference tone of this secondary wave between carrier wave and LSB, between carrier wave and USB, is equal to the original audible sound wave. On the other words, the emitted ultrasound wave is demodulated into original audible sound wave because of the nonlinear interaction. The modulated ultrasound wave v_{AM} by audible sound wave is calculated as Eqs. (1), (2).

$$v_{AM} = V_{cm}(1 + mV_S(t))V_C(t), \quad (1)$$

$$m = \frac{V_{sm}}{V_{cm}}, \quad (2)$$

where, V_{cm} represents maximum amplitude of carrier wave, m is amplitude modulation factor, V_{sm} represents maximum amplitude of audible sound wave, $V_S(t)$ is audible sound wave, $V_C(t)$ is carrier wave. Based on this method, parametric loudspeaker with the higher directivity characteristic is realized.

Steering for distance perception with conventional loudspeaker

Phase control of each output with conventional loudspeaker array enables to form acoustic focal point based on acoustic interference. Then listener perceives focal point as acoustic sound image in rear of focal point [3]. Because of concentration of direct sound energy, reverberant sound energy is relatively reduced compared with utilizing single loudspeaker. Therefore acoustic sound image is formed in space. Also, control of focal point distance is equal to control of sound image distance. Figure 1 shows steering system for distance perception with conventional loudspeaker array. Dn represents each delay of output of each conventional loudspeaker in Fig. 1. As problem, the huge number of conventional loudspeakers is required and physical restriction resides with this system for focal point because the acoustic sound which is emitted with conventional loudspeaker widely spreads.

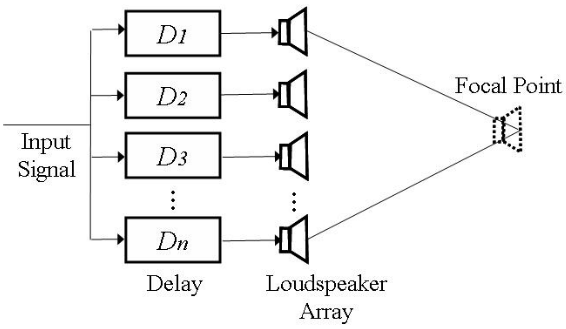


Figure 1. Steering system for distance perception with conventional loudspeaker array

Acoustic sound image with reflective audio spot

Figure 2 shows overview of reflective audio spot with parametric loudspeaker. Direct sound wave is not transmitted to the listener, but only reflection sound wave is done because of higher directivity. Therefore the listeners may localize the acoustic sound image on the reflector. Forming acoustic focal point with single parametric loudspeaker is impossible. Thus steering the acoustic sound image on the reflector for distance perception with single parametric loudspeaker is difficult.

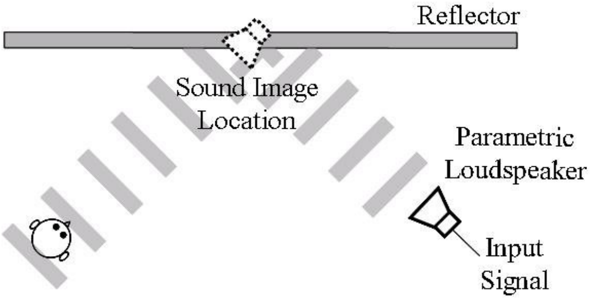


Figure 2. Overview of reflective audio spot

PROPOSED STEERING METHOD OF DISTANCE PERCEPTION WITH REFLECTIVE AUDIO SPOT

We expect form of focal point with fewer parametric loudspeakers for avoidance of physical restrict. Thus we propose steering method based on the acoustic sound image control for distance perception with parametric loudspeaker array. By designing focal and null points with adaptive digital filter, acoustic sound image control is expected to realize. MINT (Multi input/output INverce Theorem) [4] is utilized to exactly design the filter with parametric loudspeaker array. We will describe MINT in next section.

MINT (Multi input/output INverce Theorem)

MINT (Multi-input/output INverse Theorem) [4] can exactly design inverse filter to plus input way or output way in non-minimum phase. To exactly control of sound pressure levels on control points, inverse filter has to been designed for removing feature of transfer function in Fig. 3, configuration diagram of MINT. Figure 3 shows the case of controlling of sound pressure level on a control point with two loudspeakers. The output signal $Y(z)$ in Fig. 3 is calculated as Eq. (3).

$$Y(z) = (G_1(z)H_1(z) + G_2(z)H_2(z))X(z), \quad (3)$$

where, $G_1(z)$ and $G_2(z)$ represent transfer functions, $H_1(z)$ and $H_1(z)$ represent inverse filters, and $X(z)$ represents input signal. To remove feature of transfer function, filter satisfying the Eq. (4) is designed.

$$G_1(z)H_1(z) + G_2(z)H_2(z) = 1. \quad (4)$$

Equally, in the case of control of sound pressure levels on M control points, inverse filter can be exactly designed with M+1 loudspeakers. However, to realize MINT in real-time is difficult because of computational costs. Then, MINT is approximately realized with adaptive filter in next section.

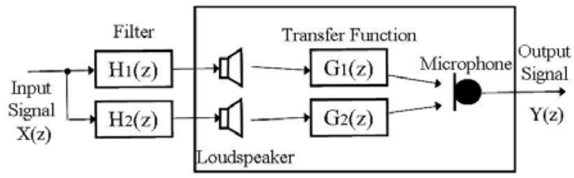


Figure 3. Configuration diagram of MINT

Adaptive filter

Adaptive filter [5] approximates output signal to desired signal. It is utilized for sound field reproduction, noise control, acoustic echo canceller, adaptive microphone array and so on [6].

Error signal is calculated by subtracting output signal and desired signal and energy of that is minimized by adaptive filter based on adaptive algorithm. Figure 4 shows configuration diagram of adaptive filter. And fix steps of filter coefficient are follows:

Step1. Set up time $k = 0$ as default of filter coefficient.

Step2. Calculate output signal $y(k)$ and error signal $e(k)$ as Eq. (5) and Eq. (6) with filter coefficient vector $\mathbf{h}(k)$, input signal vector $\mathbf{x}(k)$, desired signal $d(k)$. And T represents transposition of the matrix.

$$y(k) = \mathbf{h}(k)^T \mathbf{x}(k). \qquad (5)$$

$$e(k) = d(k) - y(k). \qquad (6)$$

Step3. Fix $\mathbf{h}(k)$ and obtain $\mathbf{h}(k+1)$ by adaptive algorithm.

Step4. Build up value of k and repeat step2 and step3, or output the conclusive filter, provided that $e(k)$ is below threshold.

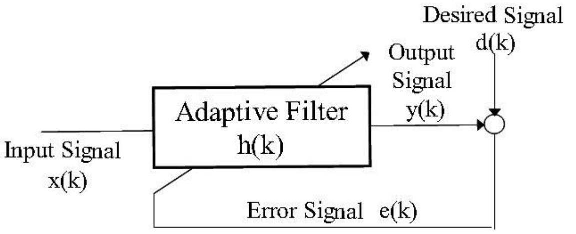


Figure 4. Configuration diagram of adaptive filter

Steering for distance perception with parametric loudspeakers and the MINT

The proposed method controls acoustic sound image distance with adaptive filter based on the MINT for distance perception. We especially try to steer acoustic sound image for the distance perception between the reflector and the listener. Figure 5 shows overview of steering method for distance perception with reflective audio spot. In Fig. 5, we put parametric loudspeaker array by arc for focal point. We firstly try to control acoustic sound image distance with three focal and null points which are located between the reflector and the listener. We thus design the adaptive filters based on the MINT for each parametric loudspeaker. The proposed system should adaptively select the optimum filters based on the distance perception. We set up three restrictions and design adaptive filters based on the acoustic sound image distance. Three restrictions are as follows:

Restriction 1 (Form acoustic sound image on MIC_1 location in Fig. 5)

Sound source design on MIC_1, null point design on MIC_2 and MIC_3.

Restriction 2 (Form acoustic sound image on MIC_2 location in Fig. 5)

Sound source design on MIC_1 and MIC_2, null point design on MIC_3.

Restriction 3 (Form acoustic sound image on MIC_3 location in Fig. 5)

Sound source design on all control points.

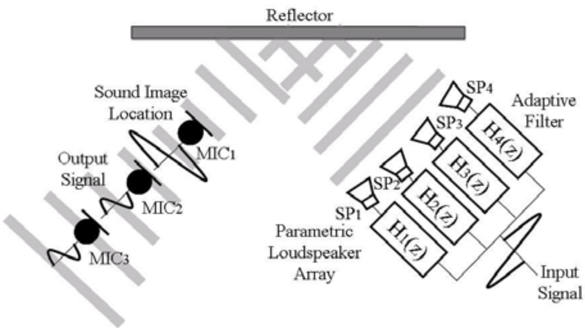


Figure 5. Overview of steering method for distance perception with reflective audio spot (utilizing **Restriction 1**)

EVALUATION EXPERIMENTS

We carried out objective and subjective evaluation experiments to confirm effectiveness of proposed method. We established experimental environment in soundproof room in Fig. 6, 7. And Table 1 shows experimental conditions. Firstly, we measured transfer functions on each control point and designed adaptive filters. Next we analysed spectra on each control point as objective evaluation experiment. Finally we carried out subjective evaluation experiment for confirming sound image localization. The listening locations for the subjects are as follows:

Listening location 1. In 150 cm distance from reflector

Listening location 2. In 225 cm distance from reflector

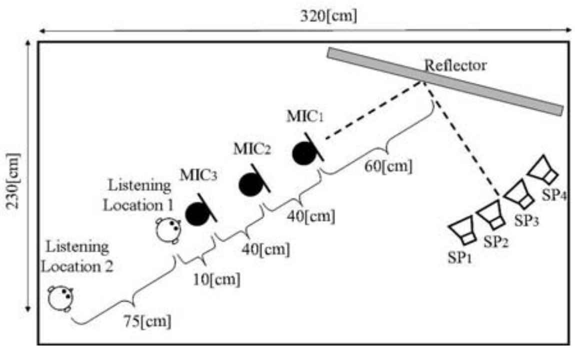


Figure 6. Experimental environment

Figure 7. Photograph of experimental environment

Table 1. The experimental conditions

Parametric loudspeaker	MSP-50E
Microphone	HOSHIDEN KUC-1333
Microphone amplifier	PAVEC Thinknet MA-2016
Loudspeaker amplifier	YAMAHA P4050
A/D converter	SONY PCM-D1
D/A converter	M-AUDIO Fast Track Ultra
Reflector	Plastic board 123×180[cm]
Recording condition	96kHz, 16bit
Ambient noise level	19.0[dBA]

Objective evaluation experiments

We carried out objective evaluation experiment to confirm effectiveness of proposed method. We analysed spectra on each control point to confirm location of focal point without any filters and to evaluate three designed adaptive filters. We set up five conditions as follows:

Condition 1. Single parametric loudspeaker (SP_2 in Fig. 5)

Condition 2. Parametric loudspeaker array without any filters

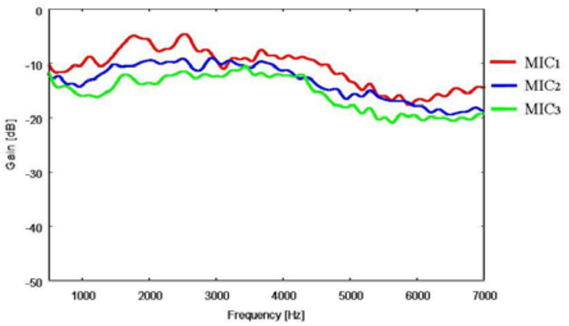
Condition 3. Parametric loudspeaker array with **Restriction 1** (sound source design on MIC_1, null point design on MIC_2 and MIC_3)

Condition 4. Parametric loudspeaker array with **Restriction 2** (sound source design on MIC_1 and MIC_2, null point design on MIC_3)

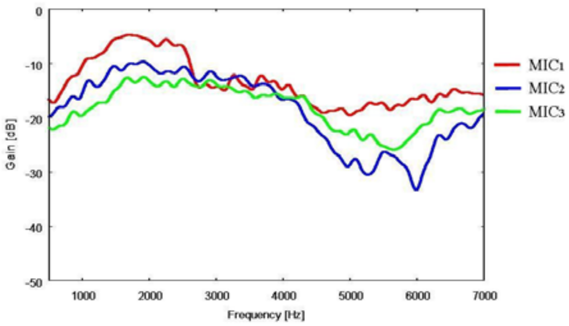
Condition 5. Parametric loudspeaker array with **Restriction 3** (sound source design on all control points)

Results by objective evaluation experiments

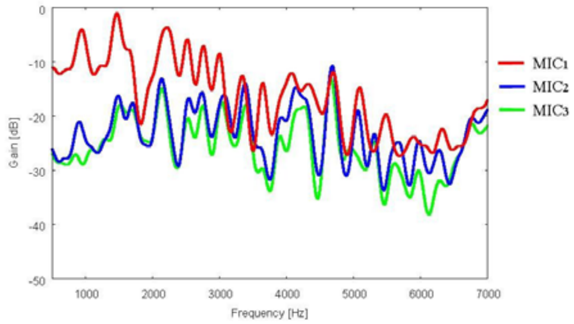
Figure 8 shows comparison with each spectrum on three control points on each condition. And Table 2 shows differences of gains of control points on each condition.



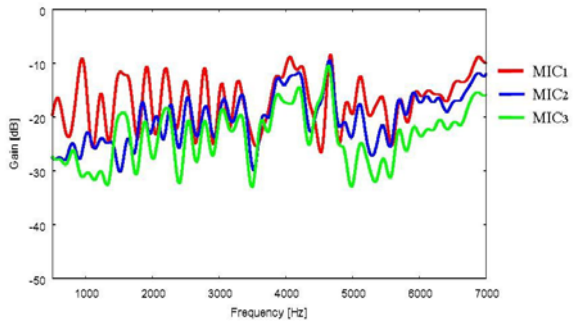
(a) Single parametric loudspeaker (SP_2 in Fig. 5)



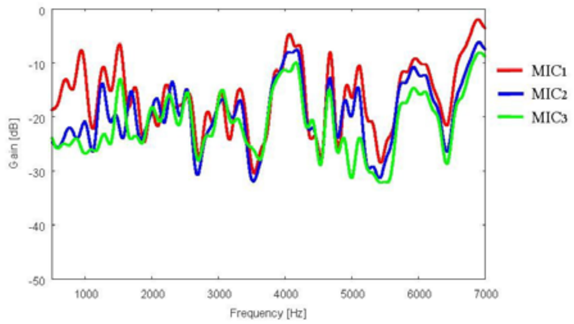
(b) Parametric loudspeaker array without any filters



(c) Parametric loudspeaker array with **Restriction 1**



(d) Parametric loudspeaker array with **Restriction 2**



(e) Parametric loudspeaker array with **Restriction 3**

Figure 8. Comparison with each spectrum on three control points on each condition

Table 2. Differences of gains of control points on each condition

	MIC_1 gain - MIC_2 gain	*MIC_2 gain - MIC_3 gain*	*MIC_1 gain - MIC_3 gain*
Single(SP_2 in Fig. 5)	2.5 [dB]	2.0 [dB]	4.5 [dB]
Without any filters	5.1 [dB]	-0.5 [dB]	4.6 [dB]
Restriction 1	6.9 [dB]	2.3 [dB]	9.2 [dB]
Restriction 2	3.1 [dB]	3.5 [dB]	6.6 [dB]
Restriction 3	2.5 [dB]	1.6 [dB]	4.1 [dB]

Discussions with objective evaluation results

Difference between MIC_1 gain and MIC_2 gain with parametric loudspeaker array without any filters is larger than that with single parametric loudspeaker in Fig. 8(a), (b) and Tab. 2. We presume this is because the appropriate arrangement of parametric loudspeakers by arc caused form of focal point on about MIC_1.

Difference is 6.9 dB between MIC_1 gain and MIC_2 gain with **Restriction 1** in Fig. 8(c) and Tab. 2. And it is 5.1 dB without any filters. Therefore we confirmed 1.8dB amount of suppression on MIC_2 by utilizing **Restriction 1**. In addition, difference is 9.2 dB between MIC_1 gain and MIC_3 gain with

Restriction 1. And it is 4.6 dB without any filters. Thus we also confirmed 4.6 dB amount of suppression on MIC_3 by utilizing **Restriction 1**. These results suggest **Restriction 1** caused forming focal point on about MIC_1 more exactly than without any filters.

Equally, **Restriction 2** and **Restriction 3** were effective. We could confirm 2.0 dB and 4.0 dB amounts of suppression on MIC_3 by utilizing **Restriction 2** from Fig. 8(b), (d) and Tab. 2**.** These results suggest focal point is on about MIC_2 with **Restriction 2**.

From Fig. 8(e) and Tab. 2, we could confirm the differences of gains are smaller as a whole with **Restriction 3**. These results suggest retaining effects by utilizing **Restriction 3** because we set up **Restriction 3** to design sound source on all control points. And these results suggest focal point is on about MIC_3 with **Restriction 3**. Therefore we confirmed that three focal and null points are designed with filters.

Subjective evaluation

We carried out sound image localization experiments as subjective evaluation experiment. The listening locations for the subjects are as described in Fig. 6.

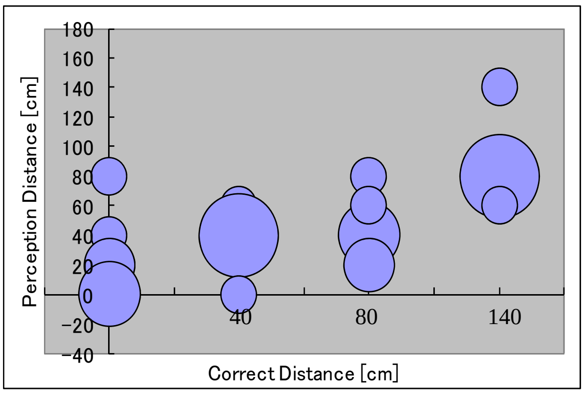
Table 3 shows correspondence of presented distance to sound source and parametric loudspeaker. We reproduced stimulus at random. The subjects answered distance where they localize acoustic sound image.

Table 3. Correspondence of presented distance to sound source and parametric loudspeaker

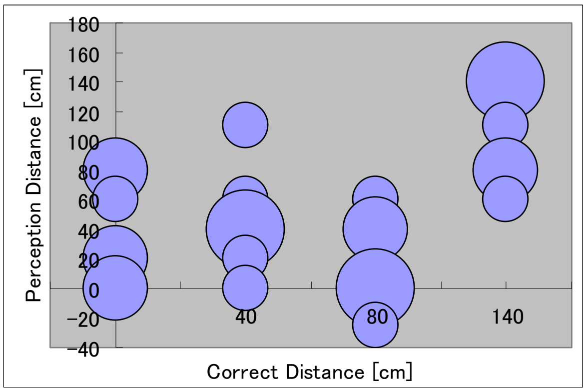
Presented Distance	*Sound Source*	*Parametric Loudspeaker*
0[cm]	White noise with restriction 3 filter	Parametric loudspeaker array
60[cm]	White noise with restriction 2 filter	Parametric loudspeaker array
100[cm]	White noise with restriction 1 filter	Parametric loudspeaker array
140[cm]	White noise with non-filter	Single Parametric Loudspeaker (SP_2 in Fig. 5)

Results by subjective evaluation experiments

Figure 9 shows results by sound image localization experiments. Table 4 and 5 show the rates of correct answer and average of perception distance in listening locations 1 and 2.



(a) Listening location 1



(b) Listening location 2

Figure 9. Results by sound image localization experiments

Table 4. Rates of correct answer and averages of perception distance in listening location 1

Presented Distance	0[cm]	40[cm]	80[cm]	140[cm]
Rate of Correct Answer	43[%]	71[%]	14[%]	14[%]
Average of Perception Distance	23[cm]	37[cm]	43[cm]	86[cm]

Table 5. Rates of correct answer and averages of perception distance in listening location 2

Presented Distance	0[cm]	40[cm]	80[cm]	140[cm]
Rate of Correct Answer	29[%]	43[%]	0[%]	43[%]
Average of Perception Distance	37[cm]	44[cm]	16[cm]	50[cm]

Discussions with subjective evaluation results

As results of Fig. 9, Tabs. 4 and 5, rates of correct answer are not higher as a whole. On the other hand, averages of perception distance show that further presented acoustic sound image distance brought subjects in listening location 1 to perceive further acoustic sound image distance as results of Tab. 4. From these, we deduce that it was difficult for subjects in listening location 1 to localize presented acoustic sound image distance, but they perceived the distance difference. We therefore confirmed that the proposed system could steer acoustic sound image for distance perception.

However, as results of Tab. 5, except 80 cm presented distance, tendency of averages of perception distance in listening location 2 is parallel with that in listening location 1. This is because it is more difficult for subjects to perceive the distance difference on each represented acoustic sound images in further location from sound image location. We expect to solve this problem by forming the focal point, sound pressure level of which increases more rapidly on the focal point with more parametric loudspeakers.

CONCLUSIONS

Reflective audio spot with parametric loudspeaker has focused recently. The listener can localize acoustic sound image on reflector. Freely controlling of acoustic sound image should lead reflective audio spot to diffuse generally. We proposed steering method based on the acoustic sound image control for distance perception with reflective audio spot with parametric loudspeaker array. We tried to steer sound image distance by designing the focal and null points. We thus designed adaptive filters based on MINT. As results of objective evaluation, we confirmed that three focal and null points are designed. In addition, as results of subjective evaluation, we also confirmed that the subjects in 150 cm distance from reflector could perceive the distance difference on each designed acoustic sound images. However no subjects in 225 cm distance from reflector could clearly perceive that one. Thus in the future, we will try to form the focal point, sound pressure level of which increases more rapidly on focal point for superior steering method for the distance perception with more parametric loudspeakers.

ACKNOWLEDGEMENTS

This work was partly supported by Grand-in-Aid for Scientific Research.

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