Reverberation Steering and Listening Area Expansion on 3-D Sound Field Reproduction with Parametric Array Loudspeaker

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***Abstract*—Recently, technologies for reproducing a 3-dimensional sound field are required for providing highly realistic sensations. Therefore, we previously proposed a system with multiple parametric array loudspeakers (PAL). PALs can design sound images on walls, ceilings, and floors by using the higher directivity of ultrasound. Thus, the proposed system can easily present incoming sound from various directions. However, it is difficult to provide a realistic sensation depending on the reverberation time. In addition, the listening area of one PAL is small. In this paper, we therefore propose two approaches for overcoming these problems. First, we propose reverberation steering with indirect electrodynamic loudspeakers and PALs. We also attempt to expand the listening area of the sound image with a curved-type PAL. As a result of evaluation experiments for each proposed approach, we could confirm the effectiveness of each approach.**

I. Introduction

In the field of virtual reality, the mixed reality (MR) system has recently been drawing attention as a technology for experiencing the virtual world [1]. This system can provide a higher realistic sensation with a combination of technologies to reproduce 3-dimensional (3-D) sound fields. Therefore, we previously proposed a system for reproducing 3-D sound fields that uses a multiple parametric array loudspeaker (PAL) [1]. The PAL, which uses an ultrasound wave, can transmit acoustic sound to a particular area called an "audio spot" [2]. It has already been used for announcements such as in museums and stations [2]. Furthermore, the PAL can form a reflective audio spot by reflecting emitted sound on walls [3]. Thus, the previously proposed system can easily present incoming sound from various directions. However, it is difficult to provide a realistic sensation depending on the reverberation time due to the sharper directivity of the PAL. In addition, the listening area is small because the reflective audio spot is narrow when using a PAL. In this paper, we therefore propose two methods for overcoming these problems. First, we propose a method that adds reverberations with indirect electrodynamic loudspeakers and direct sound with PALs. In this method, PALs of the previous system provide direct sound for the localization of sound images. The indirect electrodynamic loudspeakers provide late reverberations to provide a realistic reverberation sensation. In addition, we also propose a method for expanding the listening area with a curved-type PAL that consists of ultrasonic transducers arranged on an arc. By using it, the directivity can be steered higher or lower adapting a number of listeners. Moreover, we attempt to expand the listening area of the reflective audio spot with this PAL.

II. 3-D Sound Field Reproduction with PALs

A. *Principal of PAL*

A PAL obtains a higher directivity by utilizing an ultrasound as a carrier wave. It emits an intense amplitude modulated (AM) wave designed by amplitude modulating the carrier wave with an audible sound. The AM wave $V_{\mathrm{A}}(t)$ is derived from Eq. (1).

$$V_{\mathrm{A}}(t) = (1 + mV_{\mathrm{S}}(t))V_{\mathrm{C}}(t), \tag{1}$$

$$m = \frac{V_{\mathrm{sm}}}{V_{\mathrm{cm}}}, \tag{2}$$

$$V_{\mathrm{C}}(t) = V_{\mathrm{cm}} \cos(2\pi F t), \tag{3}$$

$$V_{\mathrm{S}}(t) = V_{\mathrm{sm}} \cos(2\pi f t), \tag{4}$$

where t represents a time index, $V_{\mathrm{C}}(t)$ and $V_{\mathrm{S}}(t)$ represent the audible sound and the carrier wave, f and F represent their frequencies, V_{cm} and V_{sm} represent their maximum amplitudes, and m represents an amplitude modulation factor. The emitted intense AM wave is self-demodulated into the audible sound by the nonlinear interaction in the air [4]. Figure 1 shows the overview of reproducing the audible sound with the PAL.

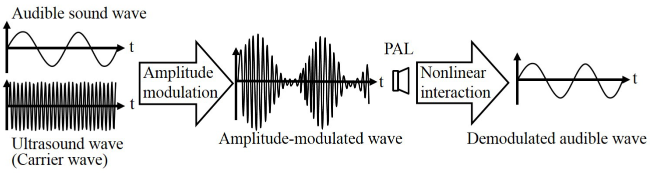


Fig. 1. Overview of reproducing the acoustic sound by the PAL.

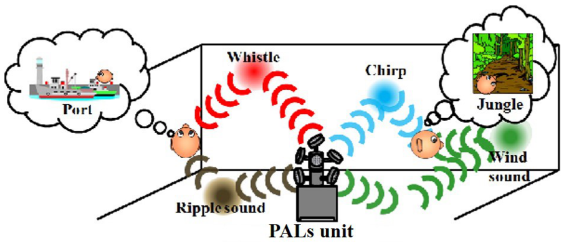
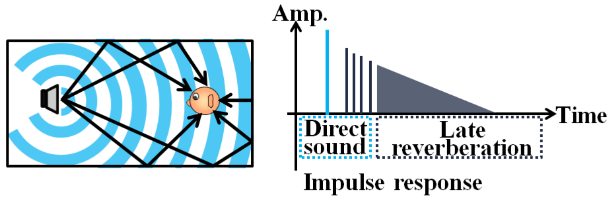
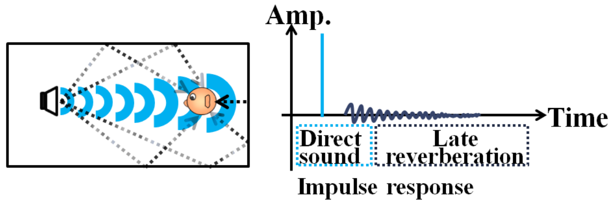


Fig. 2. Image of designing 3-D sound fields with the previous system.



(a) Impulse response with electrodynamic loudspeaker.



(b) Impulse response with PAL.

Fig. 3. Images of impulse responses with each loudspeaker.

B. Previous system

The conventional audio-visual MR system reproduces a 3-D sound field with headphones [5]. However, this system has the risk of causing a feeling of pressure on the user's head. We have therefore proposed a system for reproducing a 3-D sound field by utilizing PALs. PALs can easily design sound images and give a sense of the high sound image localization by higher directivity. Thus, the previous system can present sounds from all directions by designing sound images on walls, floors and ceilings, as shown in Fig. 2. However, the diffusion range of reflected sound by the PAL is narrower than the electrodynamic loudspeaker, as shown in Fig. 3. Thus, the previous system has a problem in that the sensation of realistic reverberation is poor. Furthermore, this system has difficulty in representing sound images to several listeners at the same time because the listening area with the PAL is narrow. Therefore, methods for overcoming these problems are required.

III. Proposed Methods

We propose two methods for overcoming problems of the previous system. Specifically, we propose a method of adding reverberation for improving the realistic sensation depending on the reverberation time. In addition, we also propose a method of expanding the listening area for simultaneous listening of several listener.

A. Proposed method for listening area expansion

Human often feel reverberation by perceiving a late reverberation and a diffuse sound. Thus, we propose a method that steers the reverberation-time with indirect electrodynamic loudspeakers arranged around the room. In this method, the PALs of the previous system transmit direct sound to listeners for high sound image localization. The indirect electrodynamic loudspeakers transmit the late reverberation and diffuse sounds for providing the sensation of reverberation. Figure 4 shows an overview of the proposed method based on adding reverberation reproduction. Moreover, we aim at providing a higher realistic reverberation sensation to listeners by steering the reverberation time. Specifically, the proposed method utilizes an acoustic signal designed by convoluting source signals and impulse response with a required reverberation time. Here, the required impulse response $\mathrm{IR}(t)$ is derived from Eq. (5).

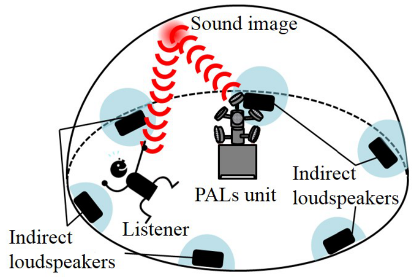


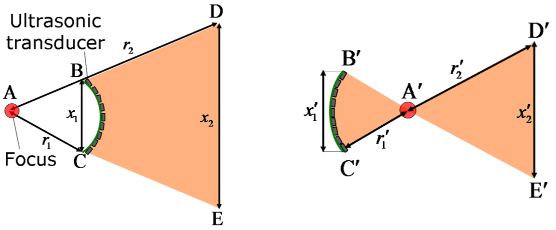
Fig. 4. Overview of the proposed method for adding reverberation sensation.

$$\mathrm{IR}(t) = n(t)e^{-\alpha t}, \tag{5}$$

where $n(t)$ represents white noise, α is constant of an exponential slope corresponding to the required reverberation time. In this paper, we experimentally determine the value of α in order to achieve the required reverberation time.

B. Method of listening area expansion

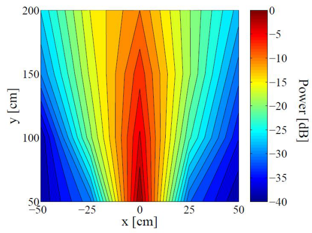
We propose a method for expanding the listening area of reflective audio spots with a curved-type PAL. Figure 5 shows the concepts of curved-type PAL. This PAL is formed by arranging ultrasonic transducers on a curved surface. In this paper, each curved-type PAL consists of 50 ultrasonic transducers. Furthermore, we use convex-type and concave-type PALs as curved-type PALs. The convex-type PAL can form a wider directivity by spreading the emission direction. In addition, the concave-type PAL can also form a wider directivity in an area farther than the focus position. In the proposed method, the curvature is determined by the radiuses r_1 and r_1' of the arc, as shown in Fig. 5. In addition, the beamwidths x_2 and x_2' depend on the radiuses r_1 and r_1' of the arc. Therefore, the curvature would be important in steering



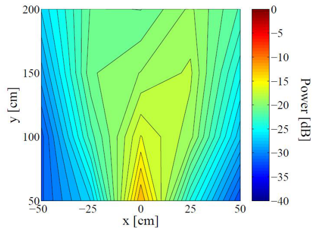
(a) Convex-type

(b) Concave-type

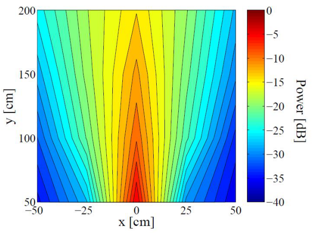
Fig. 5. Concepts of curved-type PALs



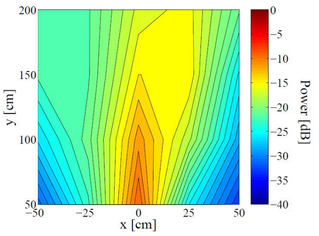
(a) Plane



(b) Convex(r_1 = 30 cm)



(c) Concave(r_1' = 30 cm)



(d) Concave(r_1' = 10 cm)

Fig. 6. Preliminary experimental results

the emission characteristics of curved-type PALs. Thus, we carried out a preliminary experiment to determine the emission characteristics of the curved-type PALs. Figure 6 shows the results in the preliminary experiment. The emission characteristics were calculated by measuring the sound pressure levels of audible sound (0 - 20 kHz). As a result, we could confirm that both the convex-type and concave-type PALs have a wider directivity than does the plane-type PAL. Furthermore, we could confirm that the concave-type PAL (r_1' = 10 cm) has a wider directivity than the concave-type PAL (r_1' = 30 cm). In the next experiments, we evaluate the effectiveness of the curved-type PAL for expanding the reflective audio spot.

IV. Evaluation Experiments

We carried out evaluation experiments for confirming each proposed method.

A. *Objective experiment on adding reverberation*

We conducted an objective evaluation experiment to confirm the effectiveness of the method for adding reverberation by comparing it with previous system. We evaluated the performance of the sound image localization and reverberation sensation by using the inter-aural cross coefficient (IACC) in the designed sound field with the proposed method [6]. Table I shows the conditions of this experiment. Figure 7 shows an arrangement of a PAL unit and indirect electrodynamic loudspeakers. In this experiment, we constructed the sound image with a PAL at three angles ($\theta = 0°, -45°, 45°$). In addition, we steered the reverberation time at 0.5 s, 1.0 s and 1.5 s as the required reverberation time. In this paper, we defined this steering time as the controlled reverberation-time (CRT). IACC demonstrates the performance of the sound image localization and the reverberation sensation by measuring the arrival time difference of an acoustic sound to each ear. A high IACC indicates a higher sound image localization, and a low IACC indicates a higher reverberation sensation. IACC is derived from Eqs. (6) and (7).

TABLE I
Conditions of the objective experiment on adding reverberation.

PAL	MITSUBISHI, MSP-50E
Indirect electrodynamic loudspeaker	BOSE, MODEL-101VM
Dummy head	NEUMANN, KU100
Sampling frequency	192 kHz
Quantization	16 bits
Carrier frequency	40 kHz
Ambient noise level	L_A = 39.6 dB
Reverberant time of experimental room	T_{60} = 0.4 s
Number of indirect electrodynamic loudspeaker	6

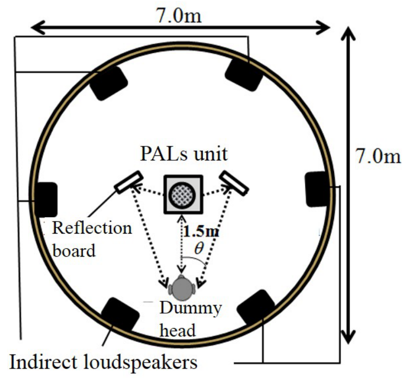


Fig. 7. Arrangement of PAL unit and indirect electrodynamic loudspeakers in the objective experiment on adding reverberation.

$$IACF_{t_1,t_2}(\tau) = \frac{\int_{t_1}^{t_2} p_l(t) \cdot p_r(t+\tau)dt}{\sqrt{\int_{t_1}^{t_2} p_l^2(t)dt \int_{t_1}^{t_2} p_r^2(t)dt}}, \quad (6)$$

$$IACC_{t_1,t_2} = \max\left|\mathrm{IACF}_{t_1,t_2}(\tau)\right|, \quad (7)$$

where $IACF$ represents a normalized inter-aural cross correlation function. $p_l(t)$ and $p_r(t)$ represent the acoustic signals to the left and right ears. t_1 and t_2 represent the measuring times, and τ represents the inter-aural time difference (-1 ms $< \tau <$ 1 ms). In this paper, we defined $t_1 = 0$ s, $t_2 = 2.0$ s. Here, the direction θ of the sound image is derived

TABLE II
IACC AND DIRECTION OF SOUND IMAGE LOCALIZATION θ WITH THE PREVIOUS SYSTEM AND THE PROPOSED METHOD

		Required direction of sound image θ		
		$-45°$	$0°$	$45°$
Previous system	IACC	0.62	0.76	0.67
	Direction of sound image θ	-46.8°	-1.2°	49.3°
Proposed method (CRT=0.5 s)	IACC	0.41	0.61	0.45
	Direction of sound image θ	-47.0°	-2.5°	48.3°
Proposed method (CRT=1.0 s)	IACC	0.41	0.61	0.45
	Direction of sound image θ	-47.0°	-2.5°	48.3°
proposed method (CRT=1.5 s)	IACC	0.41	0.60	0.45
	Direction of sound image θ	-47.0°	-2.5°	48.3°

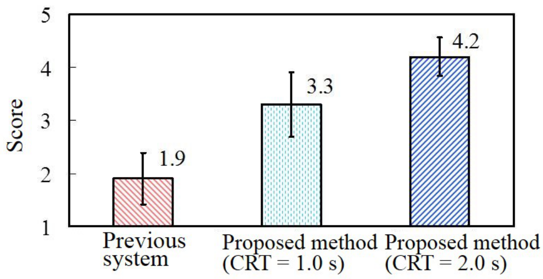


Fig. 8. Score of sound image localization in subjective experiment on adding reverberation

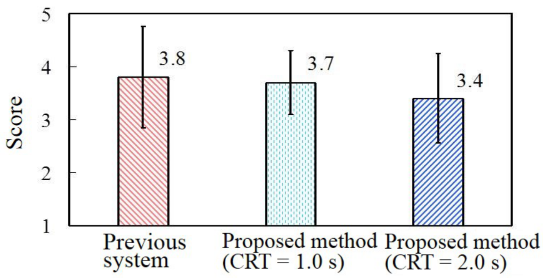


Fig. 9. Score of reverberation sensation in subjective experiment on adding reverberation

from Eq. (8).

$$\theta = \tau / \beta, \tag{8}$$

where β (ms/deg.) indicates a transformation constant. In this paper, β is defined as 8.3×10^{-3}. Therefore, we also evaluated the direction of the sound image. Table II shows the result of this experiment. From Table II, we confirmed that the IACC with the proposed method was lower than that with the previous method. This result demonstrates that the proposed method can improve the sensation of realistic reverberation. Moreover, we confirmed the proposed method constructs the sound image at the required direction despite the low IACC. Therefore, we confirmed that the proposed method can add the required reverberation without reducing the performance of the sound image localization.

B. *Subjective experiment on adding reverberation*

In this experiment, we evaluated the subjective sound image localization and the subjective reverberation sensation of the previous system and the proposed method. Subjects evaluated them on the basis of five grades. For sound image localization, grade five represents the highest localization, and grade one represents the lowest localization. For the reverberation sensation, grade five represents the highest and grade one the lowest. We steered the reverberation time at 1.0 s and 2.0 s as the required reverberation time. The number of subjects was ten, and music was employed as sound source. Figure 8 and 9 show the results of this experiment. We confirmed a small difference in the sound image localization between the previous system and the proposed method from Fig. 8. Also, we confirmed that the proposed method improves the reverberation sensation, as shown in Fig. 9. Therefore, the proposed method of adding reverberation is effective for presenting the high realistic reverberation sensation while keeping high sound image localization. In future work, we will study the arrangement and number of each loudspeaker for a higher realistic sensation.

TABLE III
CONDITIONS OF THE OBJECTIVE EXPERIMENT ON LISTENING AREA EXPANSION.

Power amplifier	YAMAHA, IPA8200
Microphone	SENNHEISER, MKH8200
A/D,D/A converter	RME, FIREFACE UFX
Sampling frequency	192 [kHz]
Quantization	16 bits
Environment	Conference room
Ambient noise level	L_A = 31.1 [dBA]
Sound source	TSP(2^{19} [point])
Curvature	Convex-type:r_1 = 10, 30 cm Concave-type:r'_1 = 10, 30 cm

C. *Objective experiment on listening area expansion*

Next, we conducted an objective experiment to verify the directional characteristics of reflected sound with the curved-type PAL. Table III shows this experimental conditions. Figure 10 shows the arrangement of the PAL and microphones in this experiment. We evaluated the proposed method for expanding the listening area with curvatures, as shown in Table III. The directional characteristics of reflected sound were calculated by measuring the sound pressure level of reflected sound at nine positions as shown in Fig. 10. Figure 11 shows the results in this experiment. As a result, we confirmed convex-type and concave-type PALs can form a wider directional characteristics of reflected sound than the plane-type PAL by employing small r_1 and r'_1. Furthermore, we confirmed the directional

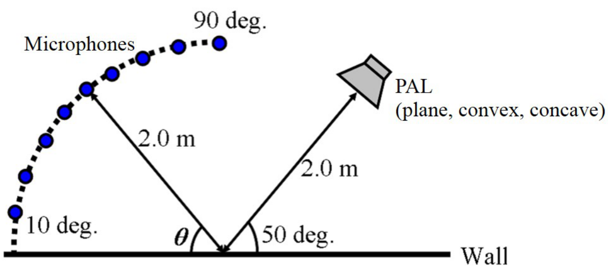


Fig. 10. Arrangement of PAL and microphones in the objective experiment on listening area expansion.

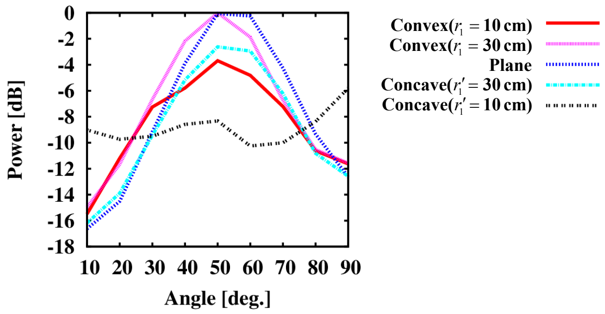


Fig. 11. Experimental results in objective evaluation experiment on listening area expansion.

characteristics of reflected sound can be widened by increasing the curvature.

D. Subjective experiment on listening area expansion

Finally, we carried out a subjective evaluation experiment on listening area expansion to subjectively evaluate the listening area of the reflective audio spot with the curved-type PAL. Table IV shows this experimental conditions. In this evaluation experiment, the subjects evaluated the sound image localization at the reflecting wall on a scale of one (no sense of sound image localization) to five (higher sense of sound image localization). The listening positions were equivalent to nine positions, which are the set microphones in Fig. 10. The evaluation at each listening position was calculated by averaging the answer of five subjects. Figure 12 shows the results in this experiment. As a result, we confirmed that the directional characteristics with the convex-type PAL (r_1 = 10 cm) was similar to that with plane-type PAL. In contrast, we confirmed the listening area of the reflective audio spot can be expanded with the concave-type PAL. The curved-type PAL was therefore effective for expanding the listening area. However, the average of evaluation with the concave-type PAL (r_1' = 10 cm) was lower than that with the plane-type PAL. The reason may be that the average of the sound pressure levels of the reflected sound with the concave-type PAL (r_1' = 10 cm) was lower than that with the plane-type PAL, as shown in Fig. 11. In the future, we will study combining each proposed method to greatly improve the system of 3-D sound field reproduction with a PAL.

V. Conclusion

In this paper, we aimed at adding the reverberation and expanding the listening area of a system with PALs for 3-D sound field reproduction. We proposed two method to achieve them. One could steer the reverberation time by reproducing late reverberation with indirect electrodynamic loudspeakers. The other could expand the listening area with a curved-type PAL. In future work, we will attempt to combine each proposed method to greatly improve the system of 3-D sound field reproduction with a PAL.

TABLE IV
Conditions of the subjective experiment on listening area expansion.

Sampling frequency	192 [kHz]
Power amplifier	YAMAHA, IPA8200
A/D,D/A converter	RME, FIREFACE UFX
Sound source	Male voice
Curvature	Convex-type:r_1 = 10 cm Concave-type:r_1' = 10 cm
Subjects	Five subjects (one female and four males)

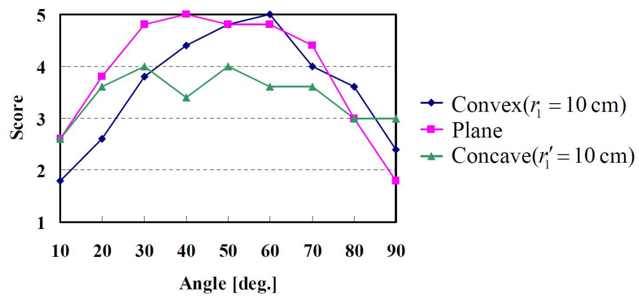


Fig. 12. Experimental results in subjective evaluation experiment on listening area expansion.

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References

[1] Y, Sugibayashi, S, Kurimoto, D, Ikefuji, M, Morise and T, Nishiura, "Three-dimensional acoustic sound field reproduction based on hybrid combination of multiple parametric loudspeakers and electrodynamic subwoofer, " Applied Acoustics, Volume 73, Issue 12, pp. 1282-1288, 2012.

[2] M. Yoneyama, J. Fujimoto, Y. Kawamo, and S. Sasabe, "The audio spotlight: An application of nonlinear interaction of sound waves to a new type of loudspeaker design, " J. Acoust. Soc. Am., Vol. 73, pp. 1532-1536, 1983.

[3] K. Hirokawa, M. Morise and T. Nishiura, "The fundamental design of reflective audio spot utilizing ultrasound loudspeaker," Proc. WESPAC2009, CD-ROM proceedings, 2009.

[4] M. Chen, Leon. Xu, Y. Cao, Limei. Xu, X. Wang, X. Li and J. Ma, "Research on an improved amplitude modulation method of audio directional loudspeaker, " IEEE ICALIP, pp. 5-9, 2008.

[5] K. Higa, T. Nishiura, A. Kimura, F. Shibata, and H. Tamura, "A two-by-two mixed reality system that merges real and virtual worlds in both audio and visual senses, " Proc. 6th Int Symp. on Mixed and Augmented Reality, pp. 203-206, 2007.

[6] T. Kamekawa and A.Marui, "Physical factors and spatial impressions of surround sound recording, " IEEE ACIS International Conference on SNPD, pp. 580-585, 2012.