Robust sound image localization for moving listener with curved-type parametric loudspeaker

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***Abstract*—Recently, technologies for reproducing a 3-D sound field are required for providing highly realistic sensations. We previously proposed a system with multiple parametric loudspeakers that have a higher directivity by using ultrasound to reproduce an audible sound in a particular area. These loudspeakers can design sound images on walls, ceilings, and floors by reflecting an emitted sound, and thus, the proposed system can easily present incoming sound from various directions. However, it is difficult to maintain the performance of sound image localization when a listener moves away from the reproduction area of the emitted sound. In this paper, we propose a sound image design method with robust localization for moving listeners. In order to constantly present the sound image localization, the method needs to steer the direction of emission in accordance with the movement of the listener. To enable this, we developed a curved-type parametric loudspeaker consisting of ultrasonic transducers arranged in an arc. The proposed method can steer the emitting direction by switching the input ultrasonic transducers without moving itself. Experimental results clearly demonstrate the effectiveness of the proposed method.**

I. Introduction

In the field of virtual reality, the mixed reality (MR) system has recently been drawing attention as a prime 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. Then, 3-D sound filed reproduction techniques are required depending on the rapid spread of them. Conventionally, multiple channel surround systems and binaural reproduction systems with the head-related transfer function (HRTF) have been proposed for this purpose[2]. These techniques can easily provide the audible realistic sensation for user. However, multiple channel surround systems often take up a lot of space due to the arrangement of multiple loudspeakers. Moreover, systems with HRTF require the user to obtain the correct HRTF by using specific equipment [3], and the measurement costs are very high. For overcoming these problems, we previously proposed a system for reproducing 3-D sound fields that uses a multiple parametric loudspeaker [4]. The parametric loudspeaker, which uses an ultrasound wave, can transmit acoustic sound to a particular area, referred to as an "audio spot" [5]. It has already been used for announcements in museums and train stations [6]. Furthermore, the parametric loudspeaker can form a reflective audio spot by reflecting an emitted sound on walls [7]. Thus, our previously proposed system can easily present incoming sound from various directions. However, it is difficult to perceive the correct direction of a sound image due to higher directivity when the listener just slightly moves away from the reproduction area. Moreover, the realistic sensation markedly decreases along with a decrease of the localization performance. One potential solution to this, using a motor for steering the direction of the parametric loudspeaker in keeping with the movement of the listener, is problematic because the driving sound may create noise. Moreover, other methods which utilize a signal processing have also been proposed for steering the beam direction [8]. These methods however is difficult to continuously steer the direction. In our study, we therefore propose a method of designing the sound image with robust localization for moving listeners by using a curved-type parametric loudspeaker. The curved-type parametric loudspeaker consists of ultrasonic transducers arranged in an arc. The proposed method can easily steer the emission direction of the ultrasound by switching input ultrasonic transducers without moving itself. In the proposed method, input ultrasonic transducers are selected on basis of a mirror method. In addition, we carry out a preliminary experiment for investigating the required number of input ultrasonic transducers for obtaining a high power and directivity. Finally, we conduct an objective experiment for confirming the effectiveness of the proposed method.

II. 3-D Sound Field Reproduction with Parametric Loudspeakers

A. *Principal of parametric loudspeaker*

A parametric loudspeaker obtains a higher directivity by utilizing an ultrasound as a carrier wave [4]. 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).

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

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

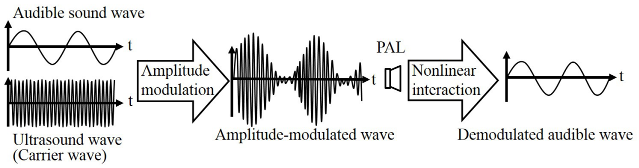

Fig. 1. Overview of reproducing the acoustic sound by the parametric loudspeaker.

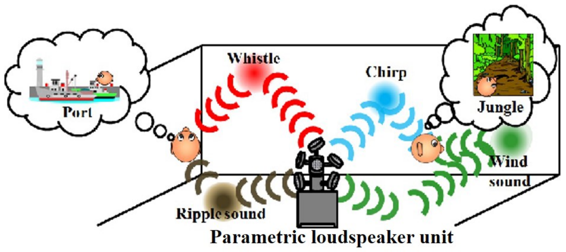

Fig. 2. Image of designing 3-D sound fields with the previous system.

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

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

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 [9]. Figure 1 shows the overview of reproducing the audible sound with the parametric loudspeaker.

B. Previous system

The conventional audio-visual MR system reproduces a 3-D sound field with headphones [10]. 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 parametric loudspeakers. They 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, a listener can't perceive the sound image at the target direction if he moves from a listening point because the parametric loudspeaker stays constant. Therefore, the system that can steer the acoustic beam without moving the parametric loudspeaker is required for overcoming this problem.

III. Proposed Method

In this paper, we propose a method for presenting a robust sound image localization for moving listener. The propose method should steer the emitting direction of the ultrasonic with the position of the listener. Here, in case of using a motor for steering the direction of the parametric loudspeaker, the driving sound of it may be a noise. We therefore propose a steering method of the emitting direction with the curved-type parametric loudspeaker.

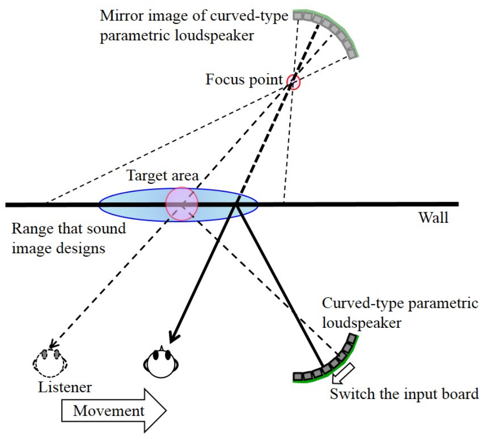

Fig. 3. Overview of the proposed method.

A. Steering of sound image direction

A proposed method designs the sound image on the target wall with the curved-type parametric loudspeaker by steering the acoustic beam direction. Figure 3 gives the overview of the proposed method. In the proposed method, the mirror method is used to determine which input boards to use. A reflected sound from the target wall is represented as a direct sound from the mirror image of the curved-type parametric loudspeaker, as shown in Fig. 3. The proposed method can design the sound image close on the target wall by using the boards intersecting a line through the listener and the focus point of a mirror image.

B. Development of the curved-type parametric loudspeaker

In our study, we develop the curved-type parametric loudspeaker for steering the emission direction of the acoustic beam. It consists of 15 boards as shown in Fig. 4. The board is mounted with ten ultrasonic transducers in a liner arrangement as shown in Fig. 5. Each board is independently controlled and arranged on arc. Mounted transducers is UT1007-Z325R produced SPL (Hong Kong) Ltd. Their diameter equals 9.9 mm, resonance frequency equals 40 kHz. Here, the parametric loudspeaker needs the arrangement of close each ultrasonic transducers. In this paper, we therefore develop the concave-type parametric loudspeaker as shown in Fig. 4. The proposed method steers the direction of the acoustic beam by switching the input board as shown in Fig 6. A follow-up range of the proposed method for the listener is defined by an arrangement and a curvature of the curved-type parametric loudspeaker. Furthermore, a resolution of the steering direction is derived from the curvature and boards number of it. In this study, we developed the curved-type parametric loudspeaker with 0.1 m radius of curvature and 15 boards. Thus, in this paper, the resolution of the steering direction of the proposed method is about 5.6 degrees. Here, if it utilizes board in singly, the directional characteristic may be too wide, and an energy of a reproduced sound may be too low. We therefore conduct

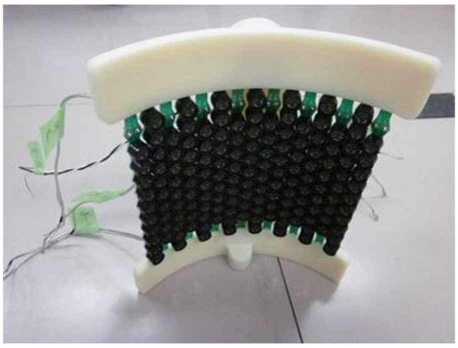

Fig. 4. Picture of the developed curved-type parametric loudspeaker.

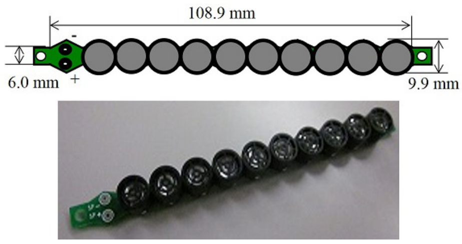

Fig. 5. Design and picture of a lined board.

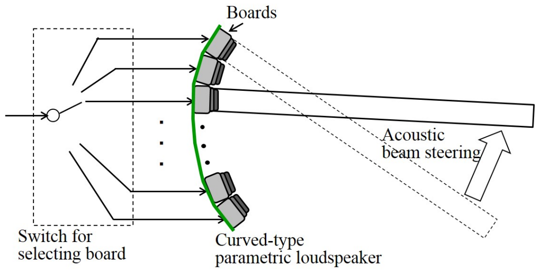

Fig. 6. Image of switching the input board.

TABLE I
THE PRELIMINARY EXPERIMENTAL CONDITIONS

Microphone	SONY, ECM-88B
Microphone amplifier	HEG, MICA-800A
Loudspeaker amplifier	YAMAHA, IPA8200
A/D, D/A converter	RME, FIREFACE UFX
Sampling rate	96 [kHz]
Quantization	16 [bit]
Carrier frequency	40 [kHz]
Place	Soundproof room
Ambient noise level	L_A = 18.8 [dB]
Sound source	White noise (2 sec)
Number of using boards	1, 2, 3 boards

a preliminary experiment for investigating the number of required boards to obtain the higher directivity and energy.

C. Preliminary experiment

For designing the sound image with the proposed method, higher-directivity and higher-energy is needed. We therefore carried out the preliminary experiment for determining the number of required number of boards at the same time. The conditions of this experiment are listed in Table I. In this experiment, we investigate the directivity and sound pressure level (SPL) of the demodulated audible sound with single board, two boards, and three boards. Specifically, we measure the spatial distribution of SPL in each conditions at 35 points as shown in Fig. 7. Figure 8 (a) $\sim$ 8 (c) show the SPL distributions on each condition. From these result, the proposed method obtains an insufficient directivity and energy with the single and two boards. On the other hand, these results indicate that higher directivity and energy is obtained by using three boards at the same time. The propose method therefore utilizes the three boards at the same time for designing the sound image.

IV. EVALUATION EXPERIMENTS

We conduct objective evaluation experiments for confirming the effectiveness of the proposed method.

A. Objective evaluation experiments

Human beings can perceive the direction of a sound image by utilizing the interaural level difference (ILD) [11]. In short, the ILD of the listener changes depending on his or her moving. In our objective experiments, we therefore evaluate the proposed method by measuring ILD. ILD is derived from Eq. (5).

$$ILD \;=\; 20\log 10\frac{\int_{t_1}^{t_2}|p_l(t)|dt}{\int_{t_1}^{t_2}|p_r(t)|dt}. \tag{5}$$

where, $p_l(t)$ and $p_r(t)$ represent the acoustic signal to the left and right ears. t_1 and t_2 represent the measurement time. In this paper, we defined $t_1 = 0$s, $t_1 = 2$s. If the sound image is constructed to the left side of the listener, the ILD is higher than zero. In this experiment, we also evaluate a performance of the sound image localization by using inter-aural cross coefficient (IACC) [12]. IACC demonstrates the performance of the sound image localization by measuring the arrival time difference of an acoustic sound to each ear. A high IACC indicates a higher sound image localization. IACC is derived from Eqs. (6) and (7).

$$\mathrm{IACF}_{t_1,t_2}(\tau) = \frac{\int_{t_1}^{t_2} p_l(t)\cdot p_r(t+\tau)dt}{\sqrt{\int_{t_1}^{t_2} p_l^2(t)dt\int_{t_1}^{t_2} p_r^2(t)dt}}, \tag{6}$$

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

where $IACF$ represents a normalized inter-aural cross correlation function. τ represents the inter-aural time difference (-1 ms $< \tau <$ 1 ms). We conducted this experiment in a soundproof room and utilized a dummy head for measuring ILD and IACC. In addition, we measure these with an electrodynamic loudspeaker mounted close on a target wall for the correct ILD and IACC. Moreover, ILD and IACC were measured without steering the direction of the acoustic beam, as the

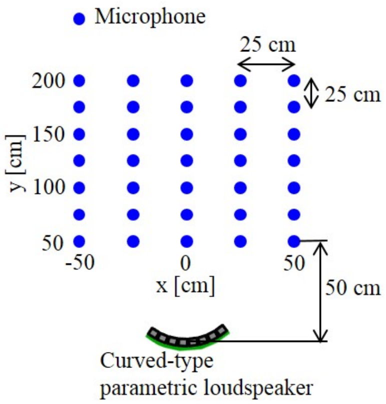

Fig. 7. Arrangement of the curved-type parametric loudspeaker and microphones.

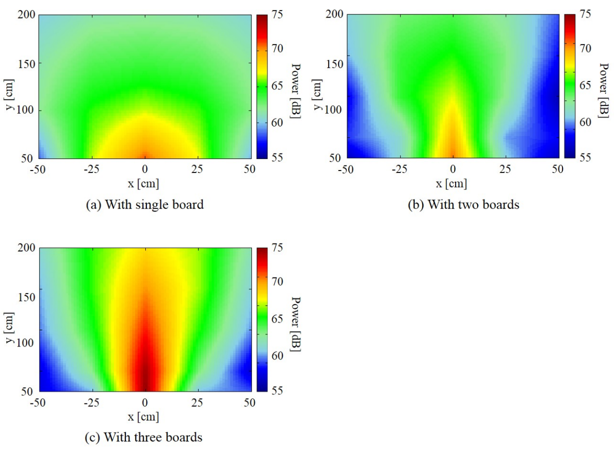

Fig. 8. The SPL distribution with each board.

conventional method does. Figure 9 shows the arrangement of each loudspeaker and dummy head. In the conventional method, the reflected sound constantly propagates to a dummy head that is 1 m from the curved-type parametric loudspeaker. Table II shows the conditions of the objective experiment. The radius of the curvature of the curved-type parametric loudspeaker is 0.1 m. If ILD and IACC with the proposed method is closer to correct ILD and IACC than that with the conventional method, it means the proposed method is more effective for presenting robust sound image localization for moving listeners.

B. Objective experimental result

Figures 10 and 11 show measured ILD and IACC with each method at each measurement point as results of objective experiments. From Fig. 10, ILD with the proposed method are closer to the correct ILD than those with the conventional method. This demonstrates that the proposed method is effective for presenting the robust sound image localization to the correct direction for moving listeners. However, ILD errors between the proposed method and method with the

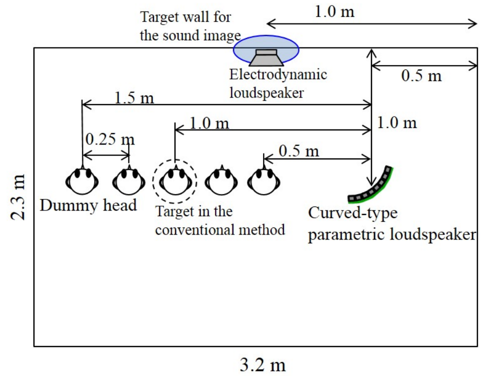

Fig. 9. Arrangement of each loudspeaker and dummy head.

TABLE II
THE OBJECTIVE EXPERIMENTAL CONDITIONS

Dummy head	Neumann, KU100
Loudspeaker amplifier	YAMAHA, IPA8200
A/D, D/A converter	RME, FIREFACE UFX
Sampling rate	96 [kHz]
Quantization	16 [bit]
Carrier frequency	40 [kHz]
Place	Soundproof room
Ambient noise level	L_A = 18.8 [dB]
Sound source	White noise (2 sec)
Measurement points	Five points

electrodynamic loudspeaker increased at 1.5 and 0.5 m. This is caused by the gap between the positions of the electrodynamic loudspeaker and the sound images with the proposed method. Therefore, a permissible range that the listener can perceive the sound image on the target wall is 25 cm from the target. From Fig. 11, IACC with the proposed method is higher than that with the conventional method. Therefore, we confirmed that the proposed method can design the sound image with higher localization of the sound image even if the listener moves. However, the proposed method provides the sound image with higher localization at points where the correct IACC is lower. This is caused by that the electrodynamic loudspeaker much emits a diffused sound such as a reverberation than the parametric loudspeaker. In future work, we will study methods for correcting the gap of the sound image and adding the diffused sound.

V. Conclusions

In this paper, we aimed at presenting robust sound image localization for moving listener. We proposed the method for designing the sound image in keeping with his moving by using the curved-type parametric loudspeaker. As a results of objective experiments, we confirmed the effectiveness of the proposed method. In future work, we will investigate subjective localization performance of the sound image with the proposed method.

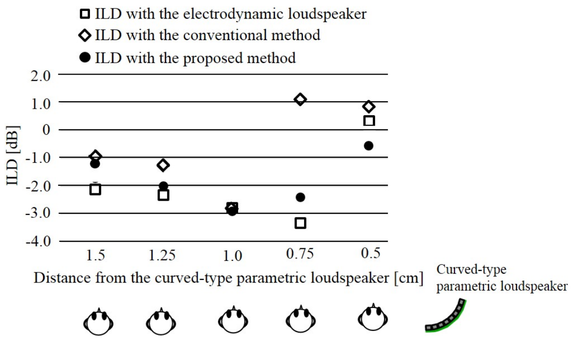

Fig. 10. ILD of each method at each measurement point.

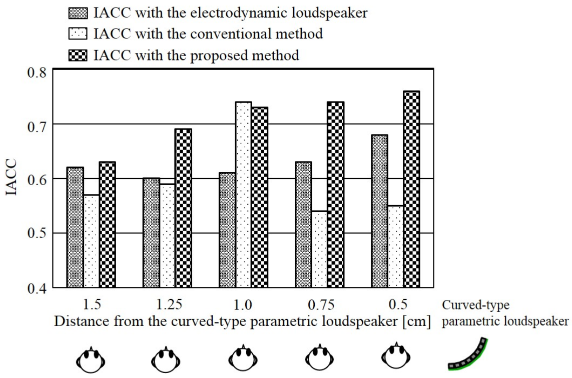

Fig. 11. IACC of each method at each measurement point.

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