Near-sound-field Propagation Based on Individual Beam-steering for Carrier and Sideband Waves with Parametric Array Loudspeaker

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***Abstract*—It is very important to provide a personal audible space (audio spot) to listeners. Near-sound-field propagation with a large scale system has been proposed to realize it. In addition, the parametric loudspeaker has been proposed in order to provide an audio spot. It is a small scale system, but the conventional parametric loudspeaker has difficulty in reproducing the audible sound only to near-field. In this paper, we therefore propose a new near-sound-field propagation based on individual beam-steering for the carrier and sideband waves using the parametric loudspeaker. In the proposed method, their waves are emitted to different directions using a parametric array loudspeaker. The method can realize the near-sound-field propagation because the audible area, which their waves are composited, is limited near to the parametric array loudspeaker. Finally, we evaluate the effectiveness of the proposed method through the evaluation experiments.**

I. Introduction

Loudspeakers and headphones are generally used for playing the music and listening the speech. Especially, the headphone is ideal candidate for listening the audible sound in the public space such as streets and office rooms. However, we need to avoid wearing the headphone because the headphone causes an oppressive feeling. In order to realize it, the loudspeaker system, which can transmit the audible sound only to an target listener, is required. Near-sound-field propagation has been proposed as the method which can transmit the audible sound only near to the loudspeaker [1], [2]. It can provide the personal audible spot without wearing the headphone even if the listener is surrounded by public people. The conventional researches [1]∼[4] propose the three-dimensional (3D) sound field reproduction based on wavefront synthesis using multiple loudspeakers (loudspeaker-array). Most of them can provide the near-sound-field with the loudspeaker-array but they require a large system with many loudspeakers.

On the other hand, a parametric loudspeaker has been proposed as a new system for 3D sound field reproduction [5]∼[7]. This is because it can form super-directivity using a single loudspeaker. The parametric loudspeaker utilizes a ultrasonic as a carrier wave which has characteristics of rectilinear propagation. It consists of a lot of small ultrasonic transducers. In addition, a parametric array loudspeaker (PAL) is proposed, and it has array structure of line-type parametric loudspeakers. In the conventional researches, beam-steering based on array signal processing technology has been introduced into PAL [8]∼[13]. However, the conventional PAL causes the noise for non-target listeners under the conditions that non-target listeners are located behind the target listener or they receive the reflected sound of acoustic beam. This is because acoustic beam is emitted as straight line. By designing the focal point in front of PAL using beam-steering, the sound pressure level of the audible sound can maximize at near the focal point. However, the audible sound is demodulated beyond the focal point and is propagated.

To solve these problems, we have previously proposed the method to design a minimum sound field called "audio-spot" using multiple parametric loudspeakers [14]. In this method, we focus on frequency characteristics of the ultrasonic sound emitted from parametric loudspeaker. The parametric loudspeaker emits an intense ultrasonic sound (wave) which is amplitude-modulated (AM) with an audible sound. The AM wave consists of carrier and sideband waves, and a difference tones between carrier and sideband waves are demodulated as the audible sound in cause of that the intense AM wave is distorted by nonlinear interaction in the air [15]. In the previously proposed method, the AM wave are separated to carrier and sideband waves. Next, the previously proposed method designs the audio spot which is the overlapped area of carrier and sideband waves by individually emitting these waves with multiple parametric loudspeakers. Therefore, the previously proposed method can realize the near-sound-field propagation by designing it near to the parametric loudspeaker. However, the previously proposed method requires multiple parametric loudspeakers and the audio spot is too small because it is about 0.1 m in diameter.

In this paper, we therefore propose a new near-sound-field propagation based on integration of the previously proposed method and beam-steering technology with digital array processing. In the proposed method, the PAL is employed. The AM wave are separated to carrier and sideband waves, and each wave is delayed with different delay time on basis of steering directions for PAL. Delayed waves are composited at each channel of PAL. Composite wave is emitted from PAL, and carrier and sideband waves are steered to different directions. In near range of PAL, the audible sound is demodulated because carrier and sideband waves are overlapped. On the other hand, in far range of PAL, silent area is designed by separating carrier and sideband waves. Consequently, the proposed

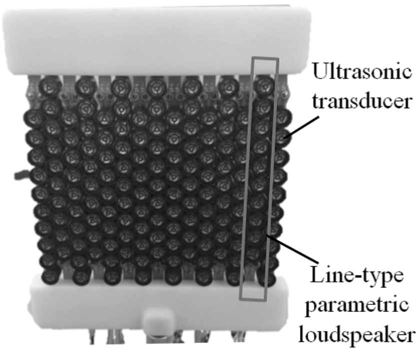


Fig. 1. Parametric array loudspeaker.

method can achieve near-sound-field propagation using PAL. In generally, the sideband wave consists of wideband spectrum. Thus, the proposed method reduces cross-modulation distortion by separating sideband wave, and steering each wave using PAL.

Finally, we confirmed the effectiveness of the proposed method through the evaluation experiment in an actual environment.

II. Principle of the parametric loudspeaker

Parametric loudspeaker utilizes an amplitude-modulated (AM) wave which is generated by modulating an amplitude of an ultrasonic sound (carrier wave) with an audible sound [15]. AM wave $x_{\mathrm{AM}}(t)$ is formulated as follows:

$$\begin{aligned} x_{\mathrm{AM}}(t) &= A_{\mathrm{C}} \cos(2\pi f_{\mathrm{C}} t) \\ &+ \frac{mA_{\mathrm{S}}}{2} \cos(2\pi(f_{\mathrm{C}} + f_{\mathrm{S}})t) \\ &+ \frac{mA_{\mathrm{S}}}{2} \cos(2\pi(f_{\mathrm{C}} - f_{\mathrm{S}})t), \end{aligned} \tag{1}$$

where t is time, f_{C} is frequency of the carrier wave, A_{C} is maximum amplitude of the carrier wave, f_{S} is frequency of the audible sound, A_{S} is maximum amplitude of the audible sound, m ($m \leq 1$) is modulation depth. In the case of $m > 1$, it is overmodulation, and the AM wave is distorted.

From, Eq. (1), the AM wave consists of a carrier frequency (f_{C}), a sum frequency ($f_{\mathrm{C}} + f_{\mathrm{S}}$), and a difference frequency ($f_{\mathrm{C}} - f_{\mathrm{S}}$). The sum and difference frequencies are referred to frequencies of the sideband wave. The audible sound is demodulated by nonlinear interaction in the air because the parametric loudspeaker emits the intense AM wave [15]. In addition, the difference tone between double sidebands generates harmonic distortion. Thus, the single sideband method is widely utilized because it can reduce harmonic distortion by demodulating the difference tone between carrier and single sideband [16].

III. Conventional near-sound-field propagation using PAL

Figure 1 shows the our developed PAL. As shown in Fig. 1, the PAL has the array structure of multiple line-type parametric loudspeakers. It can apply the array processing. In this PAL, the interval between adjacent line-type parametric loudspeakers is corresponding to the radius of the ultrasonic transducer as shown in Fig. 2.

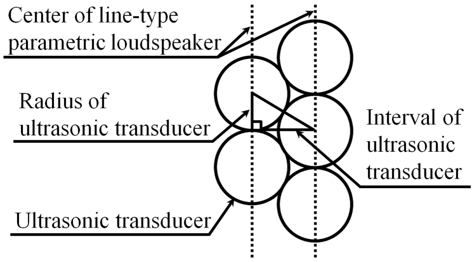


Fig. 2. Ultrasonic transducer interval.

The conventional beam-steering methods based on wave field synthesis using multiple loudspeakers (loudspeaker-array) have been proposed [17]. As the conventional method, we introduced the beam-steering method into the PAL. The beam-steering designs the focal point in front of PAL. The distance l_i $(i = 1, 2, ..., M)$ between the focal point and i-th line-type parametric loudspeaker is formulated as follows:

$$l_i = \sqrt{\left(\left(\frac{M+1}{2} - i\right) d\right)^2 + l_{\mathrm{F}}^2}, \tag{2}$$

$$d = r\sqrt{3}, \tag{3}$$

where M is number of line-type parametric loudspeaker, d is interval of adjacent line-type parametric loudspeakers, l_{F} is a foal length which is the distance from the focal point to the center point of PAL, and r is radius of a ultrasonic transducer. Thus, the delay time D_i $(i = 1, 2, ..., M)$ for i-th line-type parametric loudspeaker is calculated as follows:

$$D_i = D_0 - \frac{-l_{\mathrm{F}} + \sqrt{\left(\left(\frac{M-1}{2} - \left|\frac{M+1}{2} - i\right|\right) d\right)^2 + l_{\mathrm{F}}^2}}{c}, \tag{4}$$

where D_0 is a fixed delay and c is sound propagation speed. Equation (4) shows that the closer the line-type parametric loudspeaker comes to the center from ends, the longer the delay time is. When $x_i(t - D_i)$ is the input signal to i-th line-type parametric loudspeaker, the observed signal $y(t)$ at the focal point is calculated as follows:

$$\begin{aligned} y(t) &= \sum_{i=1}^{M} x_i\left(t - D_0 - \frac{l_{\mathrm{F}}}{c}\right) \\ &= M \cdot x_{\mathrm{AM}}\left(t - D_0 - \frac{l_{\mathrm{F}}}{c}\right). \end{aligned} \tag{5}$$

From Eqs. (4) and (5), the composite wave in the focal point has intense sound wave because all emitted waves are synchronized in the focal point. This method can form shaper directivity and achieve near-sound-field propagation by designing the focal point near to the parametric loudspeaker. However, the audible sound spreads to a large area because it is demodulated beyond the focal point. Therefore, the

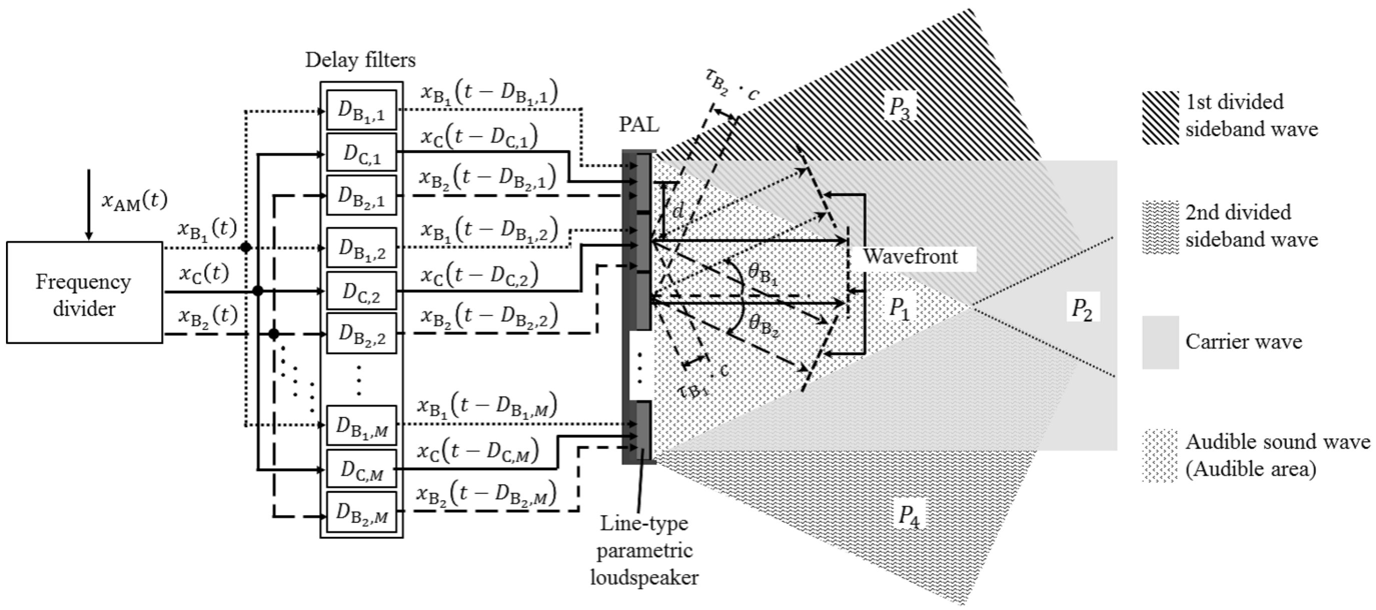


Fig. 3. Overview of the proposed method (number of sideband division: 2).

conventional method has difficulty in highly damping the acoustic sound.

IV. Suggestion of near-sound-field propagation based on using individual beam-steering for carrier and sideband waves with PAL

In this section, we propose a new near-sound-field propagation based on using individual beam-steering for carrier and sideband waves with PAL. Figure 3 shows overview of the proposed method (number of sideband division: 2). In Fig.3, t is time, $x_{\mathrm{AM}}(t)$ is the AM wave, $x_{\mathrm{C}}(t)$ is the carrier wave, $x_{\mathrm{B}_1}(t), x_{\mathrm{B}_2}(t)$ are first and second divided sideband waves, the letter C denotes the carrier wave, the letter B_1 denotes the first divided sideband, the letter B_2 denotes the second divided sideband, θ_k $(k = \mathrm{B}_1, \mathrm{B}_2)$ is the steering direction for each divided sideband wave, τ_k $(k = \mathrm{B}_1, \mathrm{B}_2)$ is the delay time of each divided sideband wave emitted by adjacent line-type parametric loudspeakers, M is number of line-type parametric loudspeakers, and $D_{k,i}$ $(k = \mathrm{C}, \mathrm{B}_1, \mathrm{B}_2, i = 1, 2, ..., M)$ is the delay time of carrier or each sideband wave emitted by i-th line-type parametric loudspeaker.

Section IV-A describes detail of how to divide the sideband wave. Also, the proposed method utilize the PAL as shown in Fig. 1. As shown in Fig. 3, the proposed method divides the AM wave $x_{\mathrm{AM}}(t)$ into the carrier wave $x_{\mathrm{C}}(t)$ and the multiple sideband waves $x_{\mathrm{B}_1}(t), x_{\mathrm{B}_2}(t)$.

Thus, the AM wave $x_{\mathrm{AM}}(t)$ is reformulated as follows:

$$x_{\mathrm{AM}}(t) = x_{\mathrm{C}}(t) + \sum_{\kappa=1}^{K} x_{\mathrm{B}_\kappa}(t), \tag{6}$$

where $x_{\mathrm{B}_\kappa}(t)$ is k-th divided sideband, K is number of frequency division (Figure 3 shows the case of $K = 2$). $x_{\mathrm{B}_k}(t)$ is input to the delay filters for all line-type parametric loudspeakers. The delay filters are designed by algorithm of delay-and-sum array [9]∼[12]. Delay-and-sum array calculates the delay time $D_{k,i}$ $(k = \mathrm{C}, \mathrm{B}_1, \mathrm{B}_2, ..., \mathrm{B}_K, i = 1, 2, ..., M)$ for i-th line-type parametric loudspeaker as follows:

$$D_{k,i} = D_0 - (i-1) \cdot \tau_k, \tag{7}$$

$$\tau_k = \frac{d \sin(\theta_k)}{c}, \tag{8}$$

where D_0 is the fixed delay, θ_k $(k = \mathrm{C}, \mathrm{B}_1, \mathrm{B}_2, ..., \mathrm{B}_K)$ is the steering direction for carrier or each divided sideband wave, τ_k $(k = \mathrm{C}, \mathrm{B}_1, \mathrm{B}_2, ..., \mathrm{B}_K)$ is the delay time of carrier or each divided sideband wave emitted by adjacent line-type parametric loudspeakers. Each delayed wave $x_k(t - D_{k,i})$ $(k = \mathrm{C}, \mathrm{B}_1, \mathrm{B}_2, ..., \mathrm{B}_K, i = 1, 2, ..., M)$ is emitted from each line-type parametric loudspeakers as follows:

$$y_i(t) = x_{\mathrm{C}}(t - D_{\mathrm{C},i}) + \sum_{\kappa=1}^{K} x_{\mathrm{B}_\kappa}(t - D_{\mathrm{B}_\kappa,i}), \tag{9}$$

where $y_i(t)$ is the output signal emitted at i-th line-type parametric loudspeaker.

The composite wave of these sound is synchronized at each steering direction. Therefore, acoustic beams are steered to each steering direction θ_k. The observed sound $x_{P_1}(t)$ in the area (P_1) of Fig. 3 is calculated as follows:

$$\begin{aligned} x_{P_1}(t) &\approx x_{\mathrm{C}}(t - D_0 - D_{P_1}) + \sum_{\kappa=1}^{K} x_{\mathrm{B}_\kappa}(t - D_0 - D_{P_1}) \\ &= x_{\mathrm{AM}}(t - D_0 - D_{P_1}), \end{aligned} \tag{10}$$

where D_{P_1} is the delay time between the observed point and PAL in the area (P_1). In Eq. (10), the approximation for delay time is applied because the wavelength of ultrasonic is very narrow and is about 0.85 mm. Equation (10) shows that the

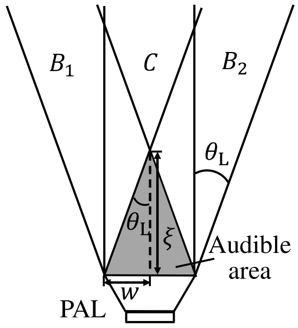


Fig. 4. Audible area designed by the proposed method (number of sideband division: 2).

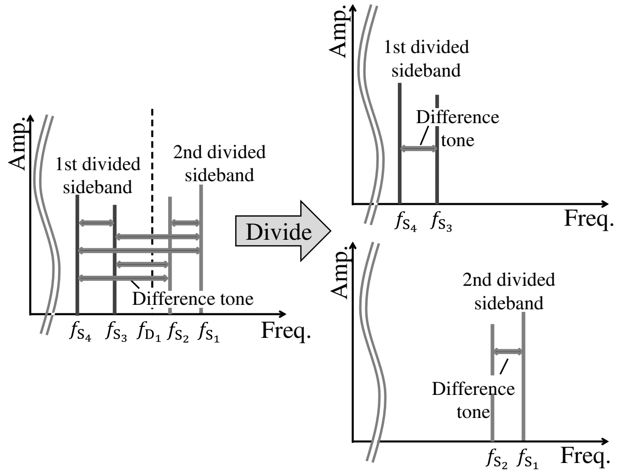


Fig. 5. Overview of how to divide the sideband wave (number of sideband division: 2).

audible sound is demodulated in the area (P_1) of Fig. 3 because acoustic beams of $x_C(t)$, $x_{B_1}(t)$ and $x_{B_2}(t)$ are overlapped in this area. On the other hand, The observed sound in the area ($P_2 \sim P_4$) of Fig. 3 is not demodulated because it consists of a carrier wave or single divided sideband wave. Thus, the proposed method can achieve near-sound-field propagation to the area (P_1) because the areas ($P_2 \sim P_4$) are silent.

Figure 4 shows overview of the audible area designed by the proposed method (number of sideband division: 2). In Fig. 4, C is the acoustic beam of the carrier wave, B_1 is the acoustic beam of the first divided sideband wave, B_2 is the acoustic beam of the second divided sideband wave, w is width of PAL, ξ is depth of the audible area, θ_L is angle of maximum steering direction for all sideband waves. ξ is calculated as follows:

$$\xi = \frac{w}{\tan(\theta_L)}. \quad (11)$$

From Fig. 4 and Eq. (11), x is corresponding to w and θ_L. This shows that the proposed method can change the size of the audible area by changing θ_L. In addition, the actual parametric loudspeaker has the radiation angle which is about $10^\circ \sim 15^\circ$. Thus, the depth ξ' of the audible area with the radiation angle is calculated as follows:

$$\xi' = \frac{w}{\tan(\theta_L - \theta_R)}, \quad (12)$$

where θ_R is the radiation angle.

A. How to divide the sideband wave

The sideband wave consists of wideband spectrum because the PAL is generally used for playing the music and listening the speech. Thus, the sideband wave causes the noise of cross-modulation distortion corresponding to different tones between spectra of the sideband wave [14], [18]. The proposed method reduces the cross-modulation distortion because the noise contaminates silent area. Therefore, we employ the amplitude modulation with single sideband (AM-SSB) [16]. Figure 5 shows overview of how to divide the sideband wave into two parts in the frequency domain. In Fig. 5, the first divided sideband is upper frequency band than the division frequency (f_{D_1}), and the second divided sideband is lower frequency band than f_{D_1}. Also, two sidebands are lower than the carrier frequency because we employ the lower sideband as AM-SSB.

TABLE I
EXPERIMENTAL EQUIPMENT.

Ultrasonic transducer	UT1007-Z325R
Power amplifier	YAMAHA, IPA8200
Microphone	SONY, ECM-88B
Microphone amplifier	Thinknet, MA-2016C
A/D, D/A converter	RME, Fireface UFX
D/A converter	RME, M-32 DA

K sideband division is formulated as follows:

$$x_{AM}(t) = x_C(t) + \sum_{\kappa=1}^{K} x_{B_\kappa}(t), \quad (13)$$

$$x_{B_\kappa}(t) = \int_{f_C - f_{D_\kappa}}^{f_C - f_{D_{\kappa-1}}} \frac{A_f}{2} e^{j(2\pi(f_C - f)t - \theta_f)} df, \quad (14)$$

where f is frequency, K is number of frequency division, f_{D_κ} ($f_{D_0} = 0$) is κ-th division frequency for the audible sound, f_{D_K} is Nyquist frequency of the audible sound, $x_{B_\kappa}(t)$ is the κ-th divided sideband wave, and A_f and θ_f are amplitude and phase at frequency f in the frequency domain, respectively.

As shown in Fig. 5, the original sideband wave includes of multiple different tones of $f_{S_1} - f_{S_2}$, $f_{S_1} - f_{S_3}$, $f_{S_3} - f_{S_4}$ and so on. On the other hand, the divided sideband waves have the different tone of $f_{S_3} - f_{S_4}$ or $f_{S_1} - f_{S_2}$. Larger number of frequency division is, more cross-modulation distortion is reduced.

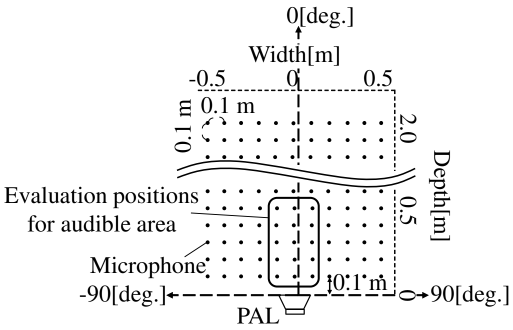


Fig. 6. Positions of microphones and PAL.

TABLE II
EXPERIMENTAL CONDITIONS.

Sampling frequency	96 kHz
Quantization	32 bits
Carrier frequency	40 kHz
Number of line-type ultrasonic transducers	15
Diameter of transducer	10 mm
Interval of line-type ultrasonic transducers	$5\sqrt{3}$ mm
Acoustic propagation speed	340 m/s
Modulation method	AM-SSB

V. EVALUATION EXPERIMENTS

A. Experimental conditions

To evaluate the spatial audible area of the proposed method, we measured distributions of the sound pressure level (SPL) of the demodulated sound by using 11ch microphone-array shown in Fig. 7. Figure 6 shows positions of microphones and PAL in the office room ($T_{60} = 0.65$ s, $L_{\mathrm{A}} = 31$ dB). PAL is positioned at (Width, Depth) = (0, 0). Angle 0° shows front of PAL. Dry source is Japanese speech (1 utterance). Table I shows experimental equipment and Table II shows experimental conditions. As shown in Fig. 1, our developed PAL is employed in this experiment. Division frequencies are manually set at 35.5 kHz, 39 kHz, and 39.5 kHz. Thus, four divided sidebands are employed:

- 1st divided sideband: 32 kHz∼35.5 kHz
- 2nd divided sideband: 35 kHz∼39 kHz
- 3rd divided sideband: 39 kHz∼39.5 kHz
- 4th divided sideband: 39.5 kHz∼39.9 kHz

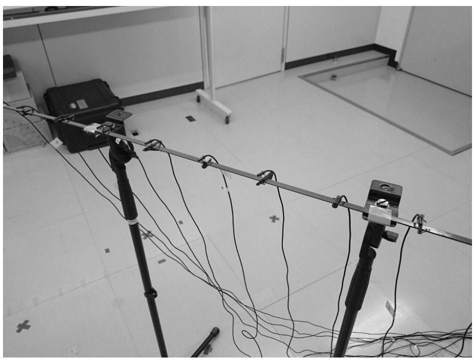


Fig. 7. Microphone-array used in the evaluation experiment.

SPL is calculated as follows:

$$\mathrm{SPL} = 10\log_{10}\left(\frac{1}{N_{f_{\max}} - N_{f_{\min}}}\sum_{n=N_{f_{\min}}}^{N_{f_{\max}}} P_{\mathrm{eval}}(n)\right), \quad (15)$$

where n is frequency index, $P_{\mathrm{eval}}(n)$ is the power of the observed audible sound, $N_{f_{\min}}$ and $N_{f_{\max}}$ are indexes of lowest frequency $f_{\min}$ and highest frequency $f_{\max}$ in the evaluated frequency band, respectively.

Also, in order to evaluate the performance of near-sound-field propagation, we calculated the SPL ratio (SPLR) between SPLs of audible and non-audible areas as follows:

$$\mathrm{SPLR} = \mathrm{SPL}_{\mathrm{audible}} - \mathrm{SPL}_{\mathrm{non-audible}}, \quad (16)$$

where $\mathrm{SPL}_{\mathrm{audible}}$ [dB] is average of SPLs at 15 positions in audible area as shown in Fig. 6, and $\mathrm{SPL}_{\mathrm{non-audible}}$ [dB] is average of every SPLs except for 15 positions in audible area. In this experiment, we employed 15 positions (0.2×0.5 m) as the spatial audible area because interaural distance is about 0.15 m and the distance between loudspeaker and ears is about 0.5 m in the case using the wearable devices. For example, wearable devices are the smart phones, the smart watches, and the laptop computers. High-SPLR shows high-performance for the near-sound-field propagation.

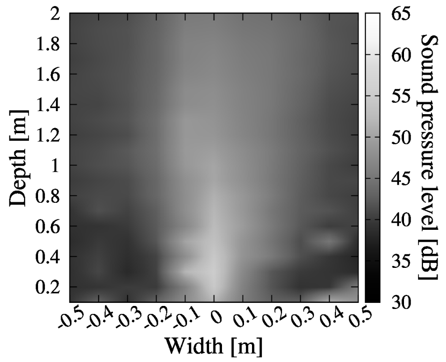
In addition, we calculated the logarithm spectral distortion (LSD) [19] in order to evaluate the sound quality of the demodulated sound. LSD is calculated as follows:

$$\mathrm{LSD} = 20\sqrt{\frac{1}{N_{f_{\max}} - N_{f_{\min}}}\sum_{n=N_{f_{\min}}}^{N_{f_{\max}}}\left(\log_{10}\frac{P_{\mathrm{orig}}(n)}{P'_{\mathrm{eval}}(n)}\right)^2}, \quad (17)$$

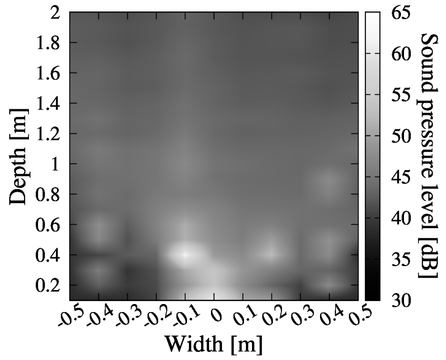
where $P_{\mathrm{orig}}(n)$ is the normalized power of the original audible sound, and $P'_{\mathrm{eval}}(n)$ is the normalized power of the observed audible sound. Smaller the LSD is, Higher the sound quality is. In this experiment, we employed $f_{\min} = 0.1$ kHz and $f_{\max} = 8$ kHz. We evaluate three methods as follows:

- Conventional parametric loudspeaker: Beam-steering is not used (Steering angle is 0°).
- Conventional method: AM wave is steered to form the focal point at focal length 0.1 m in front of PAL.
- Proposed method:
  - Carrier wave: Steering angle is 0°.
  - 1st divided sideband: Steering angle is −20°.
  - 2nd divided sideband: Steering angle is 10°.
  - 3rd divided sideband: Steering angle is −10°.
  - 4th divided sideband: Steering angle is 20°.

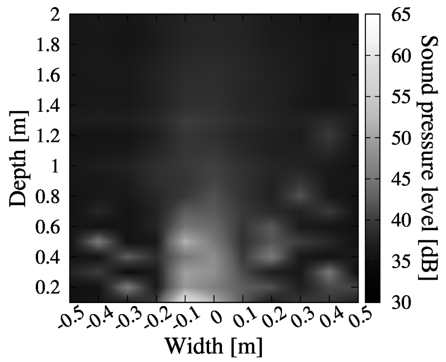
Focal length of the conventional method was determined by preliminary experiment.



(a) Conventional parametric loudspeaker



(b) Conventional method



(c) Proposed method

Fig. 8. SPL distributions of the audible sound in each condition.

B. *Experimental results for SPL, SPLR and audible distance*

Figure 8 shows SPL distributions of the audible sound for each method. In the conventional method of Fig. 8(b), we confirmed that the higher SPL was measured near the focal point compared with the conventional parametric loudspeaker of Fig. 8(a) but most of SPLs were spread. On the other hand, in the proposed method of Fig. 8(c), the higher SPL was measured in 0.5 m near the PAL, and the other SPLs were reduced in non-audible area. In Fig. 8, audible spots arise at Positions (0.4, 0.5) and (0.4, 0.6). This cause is that cross modulation would occur by reflections of room and microphone-array body.

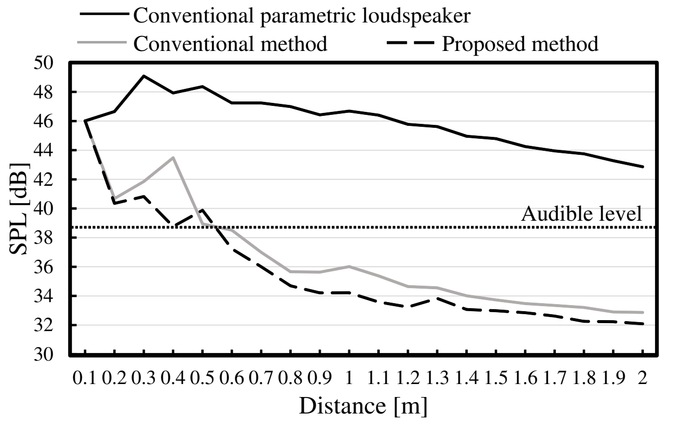


Fig. 9. Relationship between distance and SPL of the demodulated audible sound wave for each method.

TABLE III
SPLs OF ULTRASONIC IN THE PROPOSED METHOD.

Signal	SPL (Dpeth = 0.1 m)	SPL (Dpeth = 1.5 m)
Carrier	117.4 dB	114.7 dB
1st divided sideband	68.8 dB	48.9 dB
2nd divided sideband	83.9 dB	66.0 dB
3rd divided sideband	99.2 dB	76.9 dB
4th divided sideband	102.7 dB	83.9 dB

Figure 9 shows the average SPL of three points of Width $= -0.1, 0, 0.1$ m in Depth $= 0.1 \sim 2.0$ m for each method. In Fig. 9, the average SPL of each method is normalized with the average SPLs of the conventional parametric loudspeaker at Depth $= 0.1$ m. Also, in this experiment, the audible area is defined that the SPL of the demodulated sound is higher than 5 dB compared with the ambient noise level. In addition, in this experiment, the audible area is defined that the SPL of the demodulated sound is more than 5 dB, compared with the ambient noise level. More specifically, the SPL of the audible area must be over 38.8 dB because the ambient noise level is 33.8 dB. As a result of Fig. 9, the audible area of conventional parametric loudspeaker was over Depth $= 2.0$ m, and the audible areas of conventional and proposed methods were less than Depth $= 0.5$ m. From Eq. 12, the depth ξ' of the audible area with the proposed method is calculated as $\xi' = 0.4 \sim 0.75$ m. Therefore, we confirmed that conventional and proposed methods were able to achieve the near-sound-field propagation.

Figure 10 shows SPLs of ultrasonic (carrier and sidebands) and audible sound in the proposed method. Table III shows SPLs of ultrasonic in the proposed method at Depth $= 0.1$ m and 1.5 m. From Table III, we confirmed that attenuation in between Depth $= 0.1$ m and 1.5 m is that the carrier wave is 2.7 dB, and sideband waves are average 19.7 dB. Also, from Fig. 10, we confirmed that attenuation of sideband waves

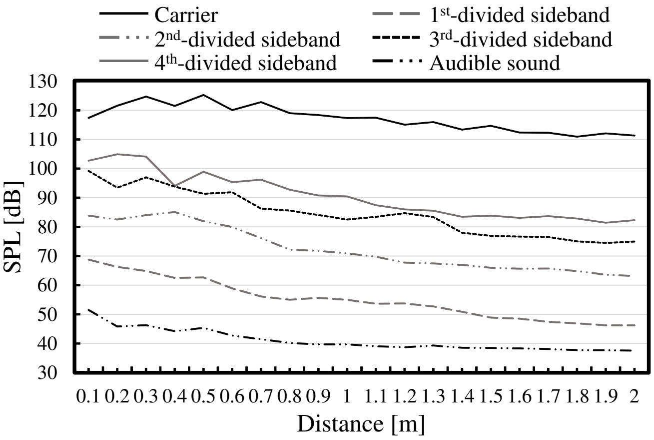


Fig. 10. Relationship between distance and SPLs of the ultrasonic and demodulated audible sound waves in the proposed method.

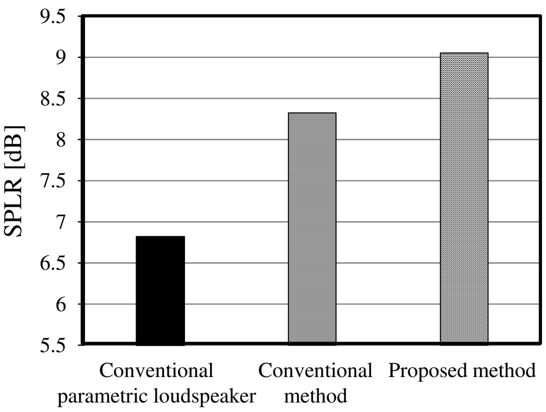


Fig. 11. SPLR of audible and non-audible areas.

is corresponding to that of the audible sound. Therefore, we confirmed that overlapped area of intense carrier and sideband waves is audible.

In Fig. 9, the demodulation distance x of the proposed method is similar to that of the conventional method. However, in the conventional method, the audible sound is spread to wider area as shown in Fig. 8. Figure 11 shows SPLR of audible and non-audible areas. Results of $\mathrm{SPL}_{\mathrm{audible}}$ were calculated as follows:

- Conventional parametric loudspeaker: 49.9 dB
- Conventional method: 51.5 dB
- Proposed method: 46.6 dB

Results of $\mathrm{SPL}_{\mathrm{non-audible}}$ were calculated as follows:

- Conventional parametric loudspeaker: 43.0 dB
- Conventional method: 43.2 dB
- Proposed method: 37.5 dB

As a result of Fig. 11, we confirmed that SPLR of the proposed method is the highest performance. Therefore, the effectiveness of the proposed method was confirmed.

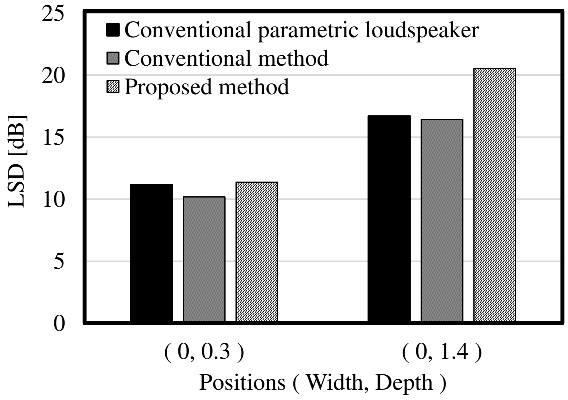


Fig. 12. LSD of each condition.

C. Experimental result for LSD

Figure 12 shows LSD calculated at Positions (0, 0.3) and (0, 1.4) for each method. From Fig. 12, LSD of the proposed method is similar to LSDs of the conventional method and the conventional parametric loudspeaker at Position (0, 0.3). Thus, we confirmed that the sound quality of the proposed method is similar to that of the conventional method. Also, at Position (0, 1.4), LSD of the proposed method is larger than that of the conventional method and the conventional parametric loudspeaker because the audible sound is distorted except for near the PAL. This suggest that demodulation of the audible sound is sufficient in audible area and is insufficient in non-audible area. Therefore, the effectiveness of the proposed method was confirmed because the performance of near-sound-field propagation is superior to the conventional method.

VI. Conclusions

In this paper, we proposed a new near-sound-field propagation based on individual beam-steering for carrier and sideband waves with PAL. As a result of evaluation experiments for SPL and LSD, the effectiveness of the proposed method was confirmed. In the evaluation experiment, the demodulated sound was small because we employed the speech signal, which is dominant in the lower frequency, as the audible sound. In future, we intend to study the determination method for steering angle and number of sideband division in order to achieve a flexible near-sound-field propagation. In addition, we intend to raise the SPL of the proposed method for various audible sound by introducing deferent modulation method into the proposed method.

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