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Development of multi-way parametric array loudspeaker using multiplexed double sideband modulation

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ABSTRACT

Parametric array loudspeaker (PAL) can achieve a sharper directivity by utilizing ultrasonic wave than conventional dynamic loudspeakers. However, PAL has difficulty reproducing low-frequency sound because it utilizes demodulation of ultrasound in the air. We have proposed the multiplexed double sideband (M-DSB) modulation for PAL, which can enhance sound pressure level (SPL) by utilizing harmonic distortion in demodulation. However, in lower frequency, sound quality by PAL with M-DSB is still insufficient compared with one by dynamic loudspeakers. Therefore, in this paper, we develop a new multi-way PAL with combining software and hardware approaches, which can achieve both sharper directivity and powerful bass sound. Multi-way PAL consists of a tweeter PAL (T-PAL) and woofer PALs (W-PALs), and each part is an aggregate of multiple ultrasonic transducers (UTs). T-PAL employs single sideband (SSB) modulation, which gives low-distortion but low-SPL. W-PAL employs M-DSB modulation, which gives high-SPL but high-distortion. In order to achieve a flatter frequency response, we conducted preliminary experiments to determine both a suitable number of UTs and an optimized arrangement for T-PAL and W-PALs. Finally, we confirmed the effectiveness of the proposed method through evaluation experiments.

Keywords: Parametric array loudspeaker, Multi-way speaker, Modulation, Hardware arrangement

1 INTRODUCTION

In recent years, parametric array loudspeaker (PAL) [1, 2] has received attention for its sharp directivity. PAL emits an intense amplitude modulated (AM) wave synthesized by modulating an ultrasonic wave with audible sounds. The emitted intense AM wave is demodulated from ultrasonic wave to audible sound by non-linear interaction in the air, and the demodulated audible wave achieves the sharp directivity of ultrasonic wave. Hence, PAL can reproduce audible sound in a particular area and is promising to be used in museums, stations and so on. However, it is difficult for PAL to reproduce bass sounds, and the sound quality is degraded by harmonic distortion [3]. Conventionally, the sound pressure level (SPL) and sound quality are considered to be influenced by the modulation method. For instance, double sideband (DSB) modulation [1] shows a higher SPL and single sideband (SSB) modulation [4] shows a better sound quality. Therefore, weighted double sideband (W-DSB) modulation is proposed in which different modulation methods are utilized in different bands with weighting factors [5]. W-DSB can realize a flatter frequency response, but it has a limitation that the SPL of demodulated sounds is extremely low. In order to attain a better performance of low-frequency reproduction, we have proposed the multiplexed double sideband (M-DSB) modulation [6], which utilizes harmonic distortions to enhance the SPL. Nevertheless, in the lower frequency, the sound quality by PAL with M-DSB is still insufficient compared with the sound quality by dynamic loudspeakers, for music listening or other applications.

In this paper, we develop a new multi-way PAL based on the modulation method and hardware design to realize a better performance of low-frequency reproduction. The proposed multi-way PAL consists of a tweeter PAL (T-PAL) and woofer PALs (W-PALs). In the proposed method, M-DSB modulation is utilized for its effectiveness on low-frequency enhancement. Moreover, focusing on the fact that the SPL of demodulated sound increases with the number of ultrasonic transducers (UTs), we allocate much more UTs for low-frequency

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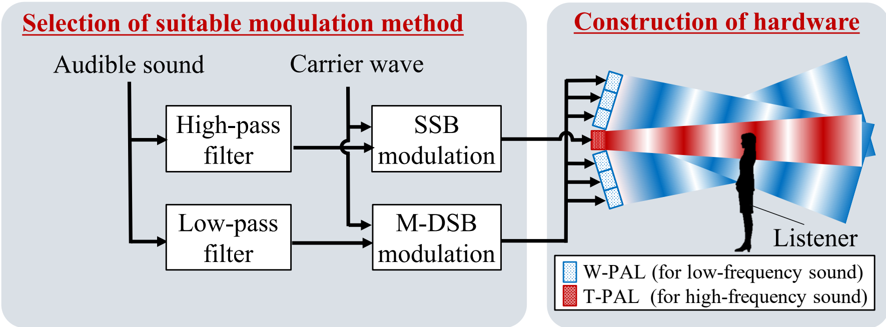


Figure 1 – Overview of the proposed multi-way PAL.

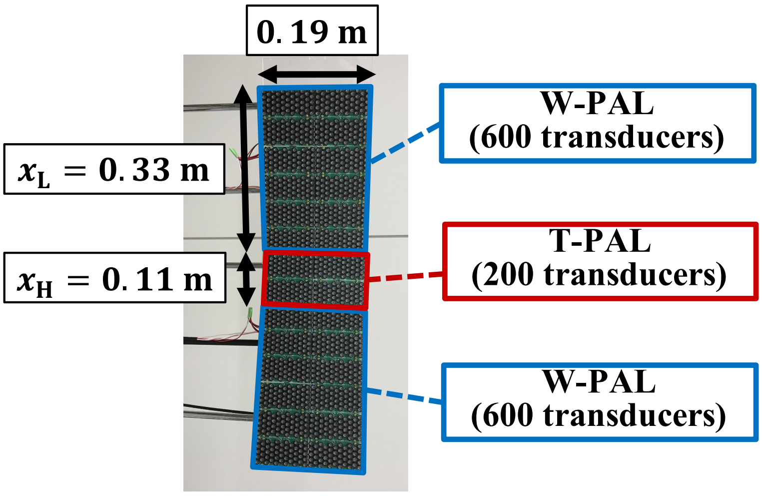


Figure 2 – Arrangement of the trial multi-way PAL.

reproduction to amplify the SPL. Therefore, with the synergy of software and hardware, a better low-frequency reproduction is promising.

2 PROPOSAL OF MULTI-WAY PARAMETRIC ARRAY LOUDSPEAKER USING MULTIPLEXED DOUBLE SIDEBAND MODULATION

2.1 Overview of Proposed Multi-way Parametric Array Loudspeaker

In this paper, we developed a multi-way PAL using M-DSB modulation. Both modulation method and hardware design are studied for a better performance on low-frequency reproduction for PAL. Figure 1 shows an overview of the proposed multi-way PAL. A trial is constructed on the basis of this proposal, and the arrangement of it is shown in Fig. 2. The proposed multi-way PAL consists of a T-PAL and W-PALs: T-PAL for the high-frequency reproduction, W-PALs for the low-frequency reproduction. We utilized different modulation methods for each part: M-DSB modulation for W-PALs, SSB modulation for T-PAL. The modulation methods of the multi-way PAL will be discussed in detail in Subsection 2.2. In addition, we study on the hardware design based on the fact that the SPL of the demodulated wave will be higher if more UTs are deployed. It is able to enhance the low-frequency significantly by allocating more UTs for W-PALs than T-PAL. The hardware design will be discussed in detail in Subsection 2.3 and the numbers of UTs for each part are determined on the basis of a preliminary experiment which will be discussed in Section 3.

2.2 Modulation Method of Proposed Multi-way Parametric Array Loudspeaker

In proposed method, we utilized M-DSB modulation for low-frequency emphasis, and SSB modulation for a better sound quality of high-frequency. As shown in Fig. 3, the audible sound is split into low-frequency sound $s_{\mathrm{L}}(t)$ and high-frequency sound $s_{\mathrm{H}}(t)$. $s_{\mathrm{L}}(t)$ and $s_{\mathrm{H}}(t)$ can be indicated as follows:

$$s_{\mathrm{L}}(t) = s(t) * h_{\mathrm{LPF}_{\Omega}}(t), \tag{1}$$

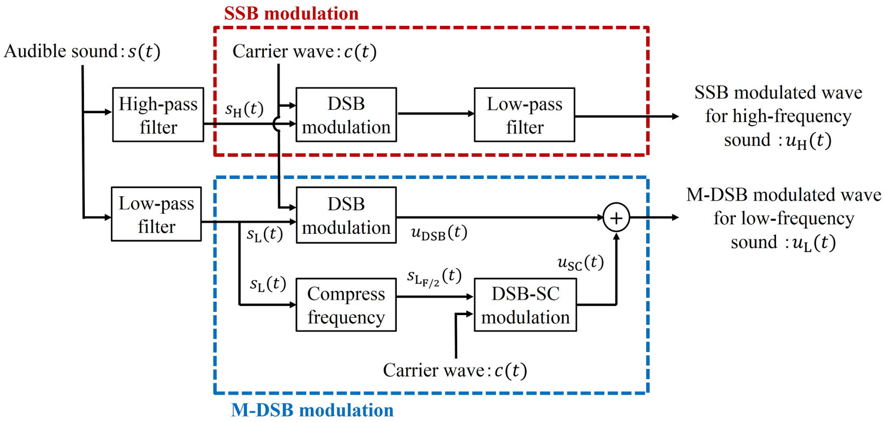


Figure 3 – Flowchart of modulation method in proposed multi-way PAL.

$$s_{\mathrm{H}}(t) = s(t) * h_{\mathrm{HPF}_\Omega}(t), \tag{2}$$

where $*$ denotes the convolution operator, $h_{\mathrm{LPF}_\Omega}(t)$ and $h_{\mathrm{HPF}_\Omega}(t)$ denote the low-pass filter and high-pass filter with a cut-off frequency Ω, and t denotes the time index.

For high-frequency, which is easy to reproduce, SSB modulation with better sound quality is utilized. A SSB modulated wave can be generated by filtering out the upper sideband of a DSB modulated wave. The SSB modulated wave which will be emitted from T-PAL can be indicated as follows:

$$u_{\mathrm{H}}(t) = \{1 + m_{\mathrm{SSB}} \cdot s_{\mathrm{H}}(t)\}c(t) * h_{\mathrm{LPF}_C}(t), \tag{3}$$

where m_{SSB} denotes the modulation factor of SSB modulation, h_{LPF_C} denotes a low-pass filter with a cutoff frequency same as the carrier frequency, and $c(t)$ denotes the carrier wave and can be indicated as follows:

$$c(t) = A_{\mathrm{C}} \cos(2\pi f_{\mathrm{C}} t), \tag{4}$$

where A_{C} and f_{C} denote the amplitude and frequency of the carrier wave.

For low-frequency, which is difficult to reproduce, M-DSB modulation is utilized because it makes use of the second harmonic distortion for low-frequency emphasis [6]. M-DSB is a combination of DSB modulation, which generates more harmonic distortions, and DSB-SC modulation, which can achieve frequency compression. As shown in Fig. 3, $s_{\mathrm{L}}(t)$ is compressed into $s_{\mathrm{L_{F/2}}}(t)$ with 1 octave. When the target sound is a cosine tone wave, $s_{\mathrm{L}}(t)$, $s_{\mathrm{L_{F/2}}}(t)$ can be indicated as follows:

$$s_{\mathrm{L}}(t) = A_{\mathrm{L}} \cos(2\pi f_{\mathrm{L}} t), \tag{5}$$

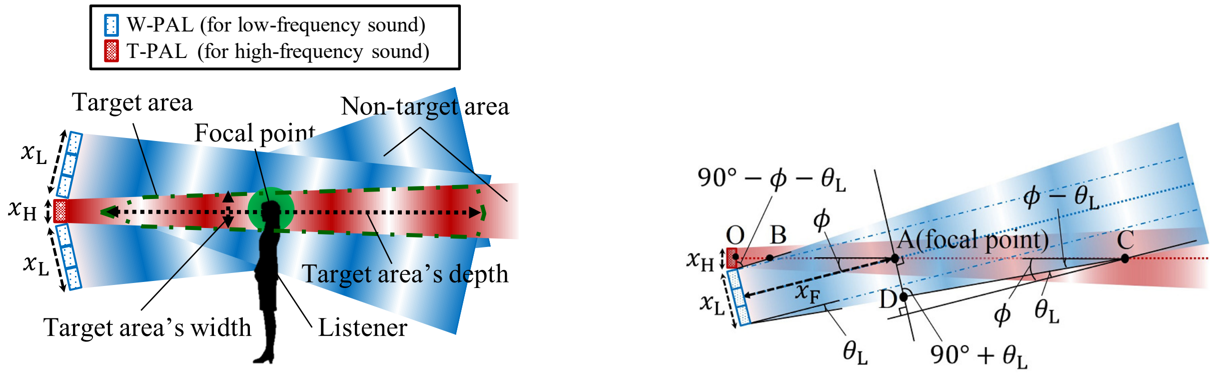
$$s_{\mathrm{L_{F/2}}}(t) = A_{\mathrm{L}} \cos(\pi f_{\mathrm{L}} t), \tag{6}$$

$s_{\mathrm{L}}(t)$ and $s_{\mathrm{L_{F/2}}}(t)$ are modulated by DSB modulation and DSB-SC modulation, respectively. And the two modulated waves are added to generate the M-DSB modulated wave. The modulated waves which will be emitted from W-PALs can be indicated as follows:

$$\begin{aligned} u_{\mathrm{L}}(t) &= u_{\mathrm{DSB}}(t) + u_{\mathrm{SC}}(t) \\ &= \{1 + m_{\mathrm{DSB}} \cdot s_{\mathrm{L}}(t) + m_{\mathrm{SC}} \cdot s_{\mathrm{L}_{F/2}}(t)\}c(t) \\ &= A_{\mathrm{C}} \cos(2\pi f_{\mathrm{C}} t) + \frac{m_{\mathrm{DSB}} A_{\mathrm{L}} A_{\mathrm{C}}}{2} \cos(2\pi(f_{\mathrm{C}} \pm f_{\mathrm{L}})t) + \frac{m_{\mathrm{SC}} A_{\mathrm{L}} A_{\mathrm{C}}}{2} \cos(2\pi(f_{\mathrm{C}} \pm f_{\mathrm{L}}/2)t), \end{aligned} \tag{7}$$

where m_{DSB} and m_{SC} denote the modulation factor of DSB and DSB-SC modulation respectively.

In Eq. (7), it is known that the M-DSB modulated wave consists of the carrier wave (frequency: f_{C}), sidebands of DSB modulated wave (frequency: $f_{\mathrm{C}} \pm f_{\mathrm{L}}$) and sidebands of DSB-SC modulated wave (frequency: $f_{\mathrm{C}} \pm f_{\mathrm{L}}/2$). Target sound (frequency: f_{L}) is demodulated from the difference of one DSB sideband and carrier wave, and also from the difference between DSB-SC sidebands. On the other hand, a half frequency distortion (frequency: $f_{\mathrm{L}}/2$) is also generated from the difference of one DSB-SC sideband and carrier wave, and from the difference of DSB sideband and DSB-SC sideband. Since the second harmonic distortion of this half frequency distortion has the same frequency with target sound, it is considered that the target sound will be enhanced in demodulation.



(a) Overview.

(b) Geometry of target area.

Figure 4 – Sectional view of relationship between multi-way PAL and demodulated sound.

2.3 Hardware Design of Proposed Multi-way Parametric Array Loudspeaker

The hardware design of proposed multi-way PAL is also studied for a better reproduction performance. The arrangement of multi-way PAL influences the size and position of target area where the sounds of T-PAL and W-PALs can be heard at the same time. The number of UTs influences the SPL of the demodulated sounds. Since PAL has a very sharp directivity, the audible areas of W-PALs and T-PAL must be overlapped. In this subsection, the parameters of the target area can be calculated theoretically. Figure 4 shows a sectional view of the relationship between demodulated sounds and the arrangement of multi-way PAL. In this proposal, as shown in Fig. 4(a), W-PALs are divided into two parts in vertical, and are closely spaced to create a focal point. We have confirmed that the demodulated sound at the focal point does not attenuate though the W-PALs are set separately in vertical. Due to the creation of the focal point, the target area becomes small, but the demodulated sound quality can be improved at the target area around the focal point. Based on the preliminary experiment in Section 3, the number of UTs is set under a proportion of 3:1:3 for upper W-PALs, T-PAL, and lower W-PALs.

In Fig. 4(b), x_F denotes the distance between multi-way PAL and focal point, x_L and x_H denote the array length of W-PALs and T-PAL respectively, θ_L and θ_H denote the directional angle of W-PALs and T-PAL respectively. The angle between W-PALs and T-PAL is denoted with ϕ and can be indicated as follows:

$$\phi = \arctan\left(\frac{x_L}{2x_F}\right) + \arctan\left(\frac{x_H}{2x_F}\right). \tag{8}$$

The distance between T-PAL and beginning of target area (line segment OB) can be indicated as follows:

$$\mathrm{OB} = \frac{x_H}{2}\tan(90° - \phi - \theta_L). \tag{9}$$

The propagation area at the focal point (line segment AD) can be indicated as follows:

$$\mathrm{AD} = \frac{x_L}{2} + x_F \tan\theta_L. \tag{10}$$

The width of the target area is the same as the propagation area of T-PAL and can be calculated with Eq. (10).

By utilizing the law of sines in triangle ACD, the distance between the focal point and the end of the target area (line segment AC) can be calculated as:

$$\mathrm{AC} = \left(\frac{x_L}{2} + x_F \tan\theta_L\right)\frac{\sin(90° + \theta_L)}{\sin(\phi - \theta_L)}. \tag{11}$$

In the case $\phi \leq \theta_L$, the point C does not exist any more, and the demodulated sounds of W-PALs overlaps with the demodulated sound of T-PAL endlessly. Except of this case, the depth of the target area (line segment BC) is limited and can be calculated as:

$$\mathrm{BC} = \mathrm{OA} + \mathrm{AC} - \mathrm{OB}, \tag{12}$$

where OB and AC can be calculated with Eq. (9) and (11), OA can be set manually because the focal point A is created by adjusting the direction of W-PALs and the position of focal point A can be controlled.

3 PRELIMINARY EXPERIMENT ON NUMBER OF ULTRASONIC TRANSDUCERS FOR MULTI-WAY PARAMETRIC ARRAY LOUDSPEAKER

3.1 Conditions of Preliminary Experiment on Number of Ultrasonic Transducers

A preliminary experiment is carried out to determine the proportion of UTs for W-PALs and T-PAL. The demodulated SPL is extremely low if the number of UTs is small, so we set 100 UTs in a certain unit of multi-way PAL. 1 unit of the proposed multi-way PAL is shown in Fig. 5. There are 4 or 5 UTs in vertical and 22 UTs in horizontal, to achieve the closest packing for a better performance of wavefront synthesis. Units adjoin on the long side and constitute W-PALs and T-PAL.

In the preliminary experiment, we first measured the power spectrum of demodulated sound. Then the proportion of UTs is calculated based on the average SPL of low-frequency and high-frequency in demodulated sound. Because of the array effect in PAL, with the increase of UTs, the SPL becomes higher than the calculation. Hence, we also calculated the average SPL with different numbers of UTs and confirmed the necessary proportion of UTs. The experimental conditions and equipment to measure the power spectrum are shown in Tables 1 and 2. The experimental conditions to measure the average power with different number of UTs are shown in Table 3. The modulated waves are normalized to reach a maximum amplitude of $(2^{15}-1)$ and emitted under the maximum permissible voltage (16 V). The necessary UTs for low-frequency is calculated with the following equation to reach the same level of demodulated SPL with high-frequency.

$$n_{\mathrm{L}} = n_{\mathrm{H}}\sqrt{\frac{P_{\mathrm{H}}}{P_{\mathrm{L}}}}. \tag{13}$$

Here, n_{L} and n_{H} denote the number of UTs for low-frequency and high-frequency respectively, P_{L} and P_{H} denote the average power of low-frequency and high-frequency respectively. P_{L} and P_{H} can be indicated as:

$$P_{\mathrm{H}} = \frac{1}{f_{max}-\Omega}\sum_{f=\Omega}^{f_{max}} P(f), \tag{14}$$

$$P_{\mathrm{L}} = \frac{1}{\Omega-f_{min}}\sum_{f=f_{min}}^{\Omega} P(f), \tag{15}$$

where $P(f)$ denote the power spectrum with frequency index f, f_{min} denotes the minimum frequency of target sound (0.1 kHz), f_{max} denotes the maximum frequency of target sound (8 kHz).

3.2 Results of Preliminary Experiment on Number of Ultrasonic Transducers

The power spectrum of demodulated sound is shown in Fig. 6. It is observed that the demodulated SPL under 1 kHz is extremely lower than that of 2, 3 kHz. Therefore, in this paper, we set $\Omega = 1$ kHz and enhance the sound under 1 kHz. Moreover, the measured average power of low-frequency (0.1~1 kHz) and

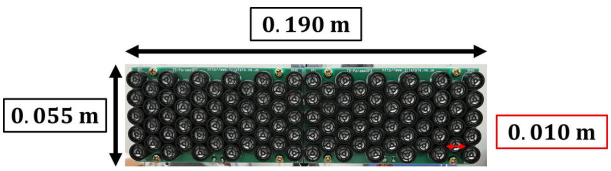


Figure 5 – One unit of the proposed multi-way PAL.

Table 1 – Experimental conditions to measure the power spectrum.

Environment	Office room (T_{60} = 650 ms)
Ambient noise level	L_A = 32.4 dB
Temperature / Humidity	24.0°C / 33.7 %
Distance between microphone and PAL	2.0 m
Sampling frequency / Quatization	192 kHz / 16 bits
Sound source	White noise (0.1~8 kHz)
Number of UTs	200
Modulation	SSB (f_{C} = 40 kHz / m_{SSB} = 1)

Table 2 – Experimental equipment to measure the power spectrum.

Ultrasonic transducer	SPL (Hong Kong) Limited, UT1007-Z325R
Power amplifier	JVC, PS-A2002
Microphone	SENNHEISER, MKH 416-P48
A/D, D/A converter	RME, FIREFACE UFX

Table 3 – Experimental conditions to measure the average power.

Crossover frequency	Ω = 1 kHz
Number of UTs	100, 200, 300, 400, 500, 600, 900, 1200 and 1500
Modulation	SSB (f_C = 40 kHz / m_{SSB} = 1), M-DSB(f_C = 40 kHz / m_{DSB} = 1, m_{SC} = 1)

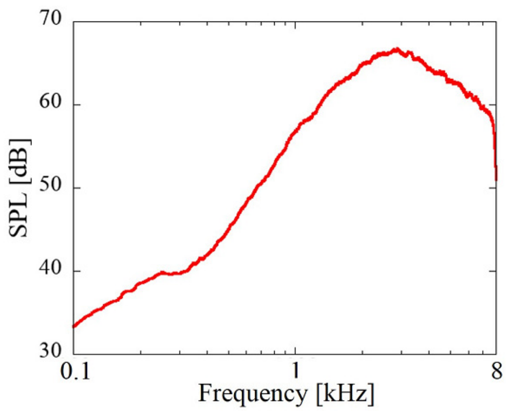


Figure 6 – Power spectrum of demodulated sound.

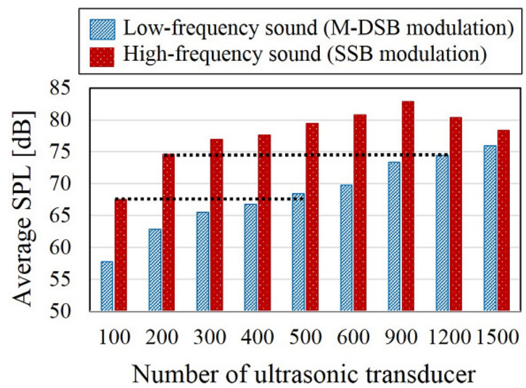


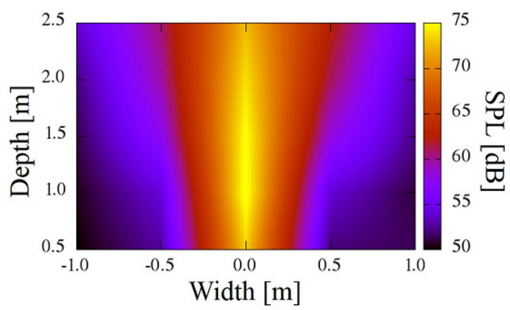
Figure 7 – Average SPL of demodulated sounds.

high-frequency (1~8 kHz) are 51.4 dB and 67.5 dB respectively. It is known that the difference in average power is 16.1 dB. From Eq. (13), it is necessary to set W-PALs 6.4 times as many UTs as T-PAL. The average SPL of demodulated sound is shown in Fig. 7. From Fig. 7, it is known that when $(n_L,\ n_H) = (500,\ 100), (1200,\ 200)$, the low-frequency and high-frequency reach the same level of SPL. Hence, in this paper, we set $(n_L,\ n_H) = (1200,\ 200)$ for the proposed multi-way PAL to achieve a higher SPL of demodulated sound.

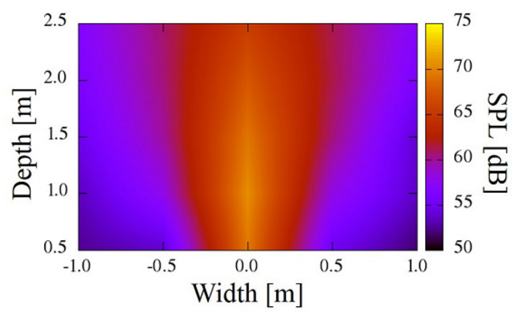
4 EVALUATION EXPERIMENT ON SOUND QUALITY FOR MULTI-WAY PARAMETRIC ARRAY LOUDSPEAKER

4.1 Conditions of the Trial Multi-way Parametric Array Loudspeaker

Based on the results of preliminary experiment in Section 3, we assembled a trial multi-way PAL as shown in Fig. 2. The number of UTs is set to $(n_L,\ n_H) = (1200,\ 200)$ as discussed, so the array length of W-PALs and T-PAL are set to $(x_L,\ x_H) = (0.33\ \text{m},\ 0.11\ \text{m})$. The position of focal point is set to x_F = 2.0 m.



(a) Woofer PAL(600 UTs, x_L=0.33 m).



(b) Tweeter PAL(200 UTs, x_H=0.11 m).

Figure 8 – SPL distribution of trial multi-way PAL.

We first carried out an experiment measuring the SPL distribution to confirm the directivity of the trial multi-way PAL. The measurement is under the same condition as shown in Tables 1 and 2. Figures 8(a) and 8(b) show the SPL distribution of W-PAL and T-PAL respectively. The directional angles are calculated from the SPL distribution, $\theta_{\mathrm{L}} = 15.8^{\circ}$ and $\theta_{\mathrm{H}} = 7.9^{\circ}$. The directivity angle is defined as the angle to the point where the SPL of the demodulated sound is attenuated 6.0 dB in the horizontal direction of the focal point. By substituting these parameters into Eq. (8), it is calculated that $\phi = 6.3^{\circ}$. Therefore, under the condition $\phi \leq \theta_{\mathrm{L}}$, it is known that the demodulated sounds of W-PALs and T-PAL will coincide all the way in the propagation direction. Moreover, the width of target area is 0.7 m, which is large enough for the size of a human head.

4.2 Conditions of Objective Evaluation Experiment on Frequency Response

An objective evaluation experiment is conducted to confirm that the proposed multi-way PAL can achieve a flat frequency response by using M-DSB modulation and multi-way hardware design. In this experiment, demodulated sounds are recorded at the focal point, and the experimental conditions and equipment are same as that shown in Tables 1 and 2. As a comparison, we prepared 4 patterns as shown in Table 4. Conventional method (W-DSB modulation) utilizes DSB modulation for low-frequency, so it is able to say that M-DSB is more effective if M-DSB can enhance low-frequency better than DSB. Then, to measure the flatness of power spectra, the average error of power spectra P_{err} is calculated as follows:

$$P_{\mathrm{err}} = \frac{1}{f_{max} - f_{min}} \sum_{f=f_{min}}^{f_{max}} |P(f) - P_{\mu}| \qquad (16)$$

where P_{μ} denotes the average of the power spectrum. A smaller value of P_{μ} implies a flatter frequency response.

4.3 Results of Objective Evaluation Experiment on Frequency Response

The power spectra and the average error of demodulated sounds at the focal point are shown in Fig. 9 and 10 respectively. The average SPL of demodulated sounds at the focal point are shown in Table 5. From Fig. 9 and Table 5, it is known that M-DSB can achieve a higher SPL than conventional DSB modulation at both low-frequency (1.1 dB) and high-frequency (1.8 dB). The second harmonic distortions are generated less at low-frequency, so the enhancement at low-frequency may be less effective than high-frequency. It is also known that the proposed method reaches a much higher SPL at low-frequency (6.0 dB) since it utilizes exclusive W-PALs. And from Fig. 10, it is observed that the proposed method achieves a lower average error than other methods, and it implies that the proposed method has a flatter frequency response than other methods. Therefore, it is confirmed that it is possible to enhance the target SPL with M-DSB modulation and multi-way hardware

Table 4 – Comparison in objective evaluation experiment.

Name	Modulation for W-PAL (low-frequency)	Modulation for T-PAL (high-frequency)
SSB	SSB	SSB
DSB	DSB	DSB
M-DSB	M-DSB	M-DSB
Proposed	M-DSB	SSB

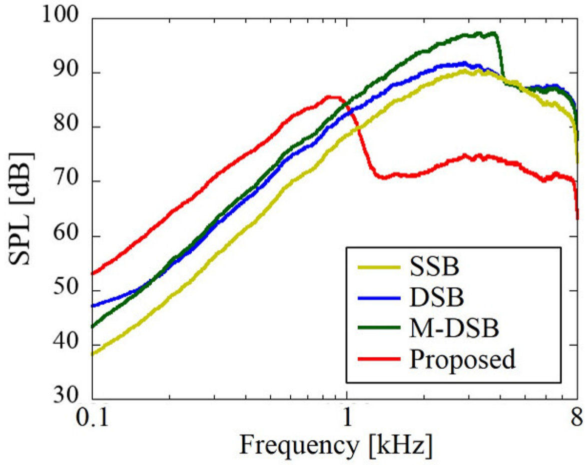


Figure 9 Power spectra of demodulated sounds at focal point.

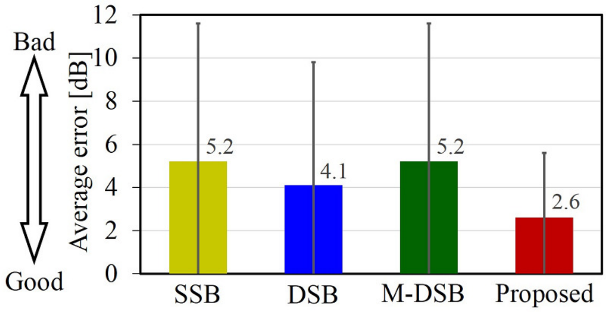


Figure 10 Average error of demodulated sounds at focal point.

Table 5 – Average SPL of demodulated sounds at focal point [dB].

	SSB	DSB	M-DSB	Proposed
Low-frequency sound	64.8	69.9	71.0	77.0
High-frequency sound	85.9	88.0	89.8	72.3

construction, especially at low-frequency. Moreover, it is confirmed that the flattest frequency response at the focal point is realized with the proposed method.

5 CONCLUSIONS

In this paper, we propose a multi-way PAL to improve the low-frequency which is difficult to reproduce. M-DSB modulation is proposed for low-frequency reproduction, and a hardware design which employs more UTs for low-frequency than high-frequency is studied as well. The effectiveness of the proposed method is confirmed by evaluation experiments, and it is known that the proposed method can achieve a flat frequency response. In the future, we will carry out an evaluation on directivity, and subjective evaluation on sound quality.

ACKNOWLEDGEMENTS

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