PHASE CONTROL OF PARAMETRIC ARRAY LOUDSPEAKER BY OPTIMIZING SIDEBAND WEIGHTS

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ABSTRACT

In this paper, we propose a method for controlling the directivity of parametric array loudspeakers (PAL) by optimizing the weights for the sideband signals. By setting the weights for the sideband signals in the single side-band (SSB) modulation to the optimum values, the directivity of the audible sound can be controlled to be ideal. The sum of squares of the difference between the directivity of the reproduced audible sound and the ideal directivity is used as an evaluation function for weight design, and the weights are updated to minimize the evaluation function by the quasi-Newton method. Through the numerical analysis of the sound pressure distribution of PAL beam control using the weights designed by the proposed method, it is demonstrated that the grating lobes are suppressed and the acoustic beam is formed to the desired direction compared with the case using the weights designed by the conventional Chebyshev function.

***Index Terms*—** parametric array loudspeaker, sound beam control, separated phased array technique, portable PAL

1. INTRODUCTION

In recent years, with the explosive spread of smartphones, the demand for video services such as YouTube has been increasing. When using such services outdoors, it is common to use earphones, but there are problems such as fatigue from wearing them for a long time and losing them. Therefore, it is thought that a parametric array loudspeaker (PAL) [1–4] with sharp directivity can be installed in a mobile terminal to form a personal audio field without using earphones.

PAL is based on the parametric acoustic array (PAA) [5–7], which is a nonlinear process in which new frequency components are generated as ultrasound waves consisting of two main frequencies propagate through a nonlinear medium. A PAL typically consists of a drive circuit and ultrasonic emitters. The drive circuit modulates the audio signal to be radiated onto the ultrasonic carrier and inputs it to the ultrasonic emitter at high amplitude. The difference component between the carrier and sideband frequencies is then generated by the PAA to reproduce the audible sound [8,9]. PALs are the most efficient directional sound sources with compact size and are used in a wide range of audio applications [3,10,11].

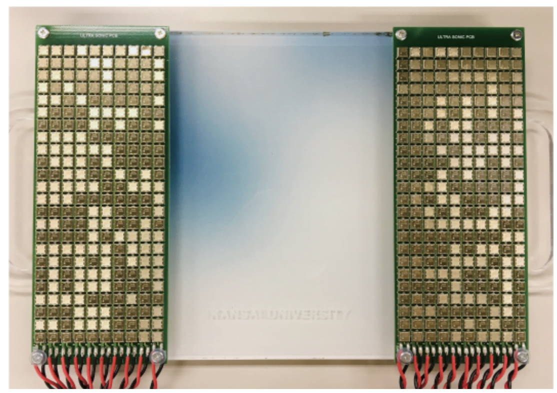

Fig. 1. Stereo PALs mounted on potable device

The system in which two PALs are implemented on a tablet device is called portable PAL [12], and its visual appearance is shown in Fig. 1. In the portable PAL, stereo sound reproduction can be achieved without earphones by utilizing the sharp directivity of the PAL. In other words, the two PALs placed on the left and right sides can transmit stereo sound to each of the user's ears independently. However, the problem is that when the user's head moves, the acoustic beams generated by the PALs are displaced from both ears. Therefore, the acoustic beams generated by the left and right PALs need to be directed to the positions of the both ears.

A method to control the directivity of PAL is steerable PAL using phased array technology [13,14]. However, when the input modulation signal to the PAL is generated by digital signal processing, the minimum steerable angle is limited by the sampling frequency. When the sampling frequency is 192 kHz, the sampling period is about 5.2 μs, and the minimum delay τ_0 is equal to the sampling period. Therefore, when the emitter spacing is $d = 5$ mm, based on the delay $\tau_n = n\frac{d}{c_0}\sin\theta_0$, the minimum steering angle θ_0 is 20.96°.

To avoid this problem, a separated phased array technique has been proposed that applies different delays and weights to the sideband frequency and the carrier frequency [15, 16]. In the separated phased array, the carrier frequency can be given a delay and weight independent of the sampling frequency, unlike the sideband frequency, and consequently the difference frequency (audible sound) can be controlled with a smaller steering angle. In conventional studies, the carrier frequency weights are designed using Chebyshev window [17] or mixed Gaussians [18], and the sideband frequency weights are designed to have wide directivity. However, since the sideband frequencies are designed to have a wide directivity, it may not be possible to direct the main lobe of the difference frequency to the desired direction. Therefore, a method of designing the weights so that the sideband frequencies also have sharp directivity through a Chebyshev window has also been proposed [12]. However, the Chebyshev window does not always design the optimal directivity because the appropriate beamwidth changes with changes in the steering angle, emitter placement and size.

In this paper, we propose a method to optimally design the weights of the sideband frequency so that the directivity of the difference frequency (audible sound) has the desired directivity. In the proposed design method, the directivity of the difference frequency is synthesized from the directivity of the carrier frequency with the weights designed by a Chebyshev window and the directivity of the sideband frequency with arbitrary weights based on the product model [19]. Then, the sideband frequency weights are optimally designed by the quasi-Newton method so that the calculated directivity of the difference frequency approaches the desired directivity set in advance. In this paper, we verify through numerical analysis that the directivity of the difference frequency can be properly controlled by using the sideband frequency weights obtained by the proposed design method.

2. SEPARATED PHASED ARRAY

The block diagram of the separated phased array is shown in Fig. 2. From Fig. 2, we can see that the structure gives different delays and weights to the carrier and sideband frequencies. When the lower sideband (LSB) of single sideband amplitude modulation (SSBAM) is used as the modulation scheme, the modulation signal of the nth channel is given by

$$S_{\mathrm{SSBAM},n}(t) = 0.5 w_{an} \cos\left[\omega_c(t-\tau_{an})\right] \quad (1)$$
$$+0.5 w_{bn} \cos\left[(\omega_c - \omega_{\text{-}})(t-\tau_{bn})\right], \quad (2)$$

where w_{an} and w_{bn} are the weights of carrier frequency and sideband frequency, ω_c and $\omega_{\text{-}}$ are angular frequency of carrier frequency and difference frequency, and τ_{an} and τ_{bn} are delays of carrier frequency and difference frequency, respectively.

As shown in Fig. 2, since the carrier frequency is independent of the sideband frequency, an appropriate delay can be given regardless of the sampling frequency. On the other

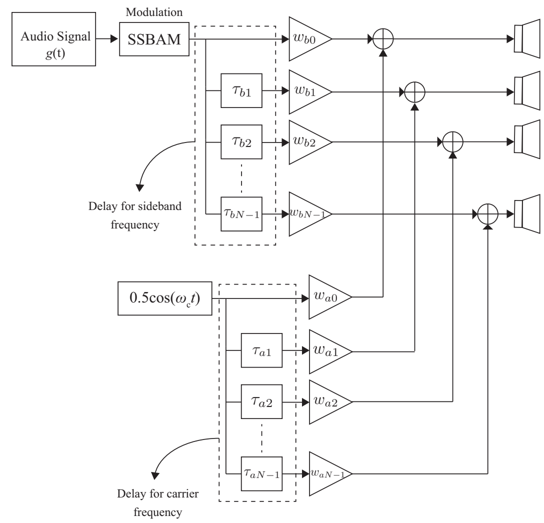

Fig. 2. Block diagram of beam control of PAL using SSBAM based on separated phased array.

hand, the delay of the sideband frequency is determined based on the sampling period T. The delays of the carrier frequency and the sideband frequency are as follows

$$\tau_{an} = n\frac{d}{c_0}\sin\theta_0, \quad (3)$$

$$\tau_{bn} = n\beta T, \quad (4)$$

where d is emitter spacing, c_0 is sound speed in air, θ_0 is steering angle, and β is an arbitrary integer, respectively.

3. DESIGN METHOD FOR SIDEBAND WEIGHTS

In the proposed weight design method, the weight of the carrier frequency, w_{an}, is designed to control the carrier beamwidth and attenuate the side lobes using a Chebyshev window. On the other hand, the weight of the sideband frequency, w_{bn}, is optimally designed so that the directivity of the difference frequency (audible sound) becomes ideal. The design procedures for each weight are described below.

Design procedure for carrier frequency weights:

1. Determine the main lobe beamwidth θ_a.
2. Calculate the sidelobe attenuation R (dB) by

$$R = 20\log\left\{T_n\left[\frac{\cos\left(\dfrac{\pi}{2(N-1)}\right)}{\cos\left(\dfrac{k_a d\sin(\theta_b/2)}{2}\right)}\right]\right\}, \quad (5)$$

where k_a is the wave number of carrier frequency, and

$$T_n(x) = \cos\left[(N-1)\cos^{-1}x\right] \quad (6)$$

is a Chebyshev polynomial.

3. The weight w_{an} is determined by using the number of arrays of ultrasonic emitters N and the sidelobe attenuation R calculated in Step 2.

4. Calculate the far-field array response using the obtained weights w_{an} as

$$H_a(\theta) = \frac{1}{N}\sum_{n=0}^{N-1} w_{an} e^{-j\omega\tau_{a0}} e^{j\omega(nd/c_0)\sin\theta}, \quad (7)$$

where $\tau_{a0} = \frac{d}{c_0}\sin\theta_0$.

5. The far-field directivity of the weighted carrier frequency $D'_{1a}(\theta) = D_{1a}(\theta)H_a(\theta)$ is calculated, where

$$D_{1a}(\theta) = \exp\left[-\frac{1}{4}(k_a a)^2 \tan^2\theta\right], \quad (8)$$

is the aperture directivity, and a is the effective source radius.

Design procedure for sideband frequency weights:

1. Based on the characteristics of the band-pass filter, determine the ideal directivity $D_{\mathrm{ideal}}(\theta)$ of the difference frequency.

2. The number of iterations is set to $i = 0$, and a uniform random numbers in the range $0 \sim 1$ are given to $w_{bn}(0)$ as the initial values.

3. Compute the far-field array response using $w_{bn}(i)$.

$$H_b(\theta, i) = \frac{1}{N}\sum_{n=0}^{N-1} w_{bn}(i) e^{-j\omega\tau_{b0}} e^{j\omega(nd/c_0)\sin\theta}. \quad (9)$$

4. Calculate the far-field directivity of the weighted carrier frequency $D'_{1b}(\theta, i) = D_{1b}(\theta)H_b(\theta, i)$.

5. Using the product model [19], calculate the directivity of the difference frequency $D_{\text{-}}(\theta, i)$.

$$D_{\text{-}}(\theta, i) = D'_{1a}(\theta)D'_{1b}(\theta, i). \quad (10)$$

6. Calculate the sum of the squares of the difference between the directivity of the difference frequency $D_{\text{-}}(\theta, i)$ and the ideal directivity of the difference frequency $D_{\mathrm{ideal}}(\theta)$ as the evaluation function $E(w_{bn}(i))$.

$$E(w_{bn}(i)) = \sum_{\theta}(D_{\text{-}}(\theta, i) - D_{\mathrm{ideal}}(\theta))^2. \quad (11)$$

7. To find the optimal weight $w_{bn,o}$ that minimizes the evaluation function $E(w_{bn}(i))$, optimization is carried out using the quasi-Newton method. That is,

$$w_{bn,o} = \arg\min_{w_{bn}} E(w_{bn}). \quad (12)$$

8. Set $i \to i + 1$, return to Step 3, and repeat until the evaluation function is minimized.

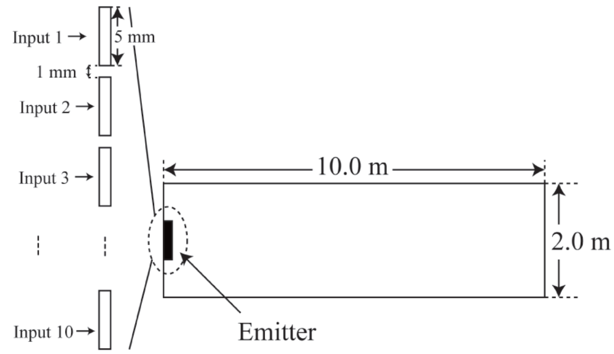

Fig. 3. Analysis space in k-wave

Table 1. Numerical analysis conditions in k-wave.

Number of array	10
Difference frequency	4 kHz
Carrier frequency	40 kHz
Modulation	SSBAM (LSB)
Steering angle	5, 10 degree
Beamwidth of CF (Proposed)	15 degree
Beamwidth of CF (Conventional)	10 degree
Beamwidth of SF (Conventional)	30 degree
Sampling frequency	192 kHz

4. ANALYSIS RESULTS

In this paper, we analyze the sound pressure distribution of PAL using the MATLAB toolbox k-wave [20–22]. The analysis space is 2 m in length and 10 m in width. 10 arrays of ultrasonic emitters with a width of 5 mm are placed, and each emitter is given an input signal adjusted by different weights and delays. The arrangement of the emitters and the analysis space are shown in Fig. 3, and the k-wave analysis conditions are shown in Table 1. In the proposed method of designing the sideband frequency weights, the desired directivity of the difference frequency is set for each steering angle of 5 degrees and 10 degrees. In the numerical analysis of the sound pressure distribution, the proposed method, which optimally designs the sideband frequency, is compared with the conventional method, which designs the sideband frequency using a Chebyshev window. The effectiveness of the proposed weight design method is verified by comparing the directivities of the two methods.

Fig. 4 and Fig. 5 show the analysis results of the sound pressure distribution for the steering angles of 5 and 10 degrees, respectively. From Fig. 4, it can be seen that the sound pressure distribution is almost the same for the conventional method and the proposed method. Next, Fig. 5 shows that the conventional method generates grating lobes with the same sound pressure level as the main lobe of the steering angle. On the other hand, in the proposed method, the grating lobe

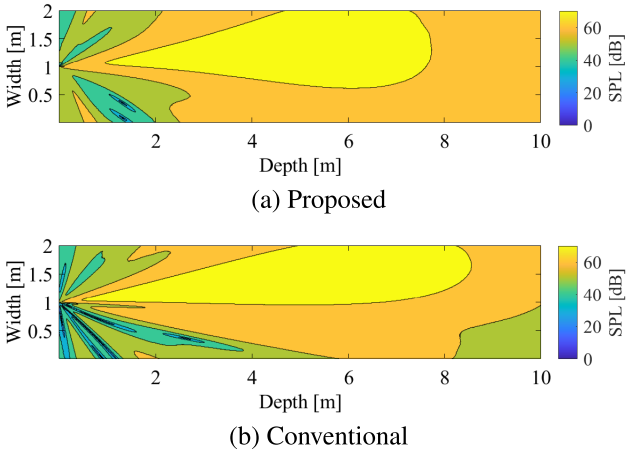

Fig. 4. Sound distribution when steering angle is 5 degree.

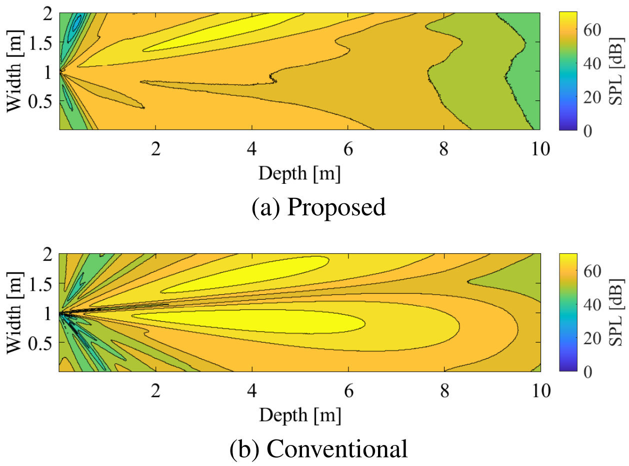

Fig. 5. Sound distribution when steering angle is 10 degree.

is suppressed.

The directivity analysis results at a distance of 2 meters from the PAL for the steering angles of 5 degrees and 10 degrees are shown in Fig. 6. It can be seen that the grating lobe of the conventional method is larger than that of the proposed method when the steering angle is 5 degrees. When the steering angle is 10 degrees, the grating lobe of the conventional method has the same sound pressure level as the main lobe. On the other hand, in the proposed method, the grating rope is completely suppressed. Here, the large grating lobes in the conventional method are caused by the fact that the beamwidths of the carrier and sideband frequencies are not properly adjusted. In the proposed method, the effect of the grating lobes is suppressed although there is a slight deviation in the radiation angle, indicating that the proposed method of designing the sideband frequency weights is effective. Moreover, the proposed method can realize a sharper main-lobe and lower side-lobe because the weights w_{bn} are designed based on the evaluation function (11) to approach the ideal directivity.

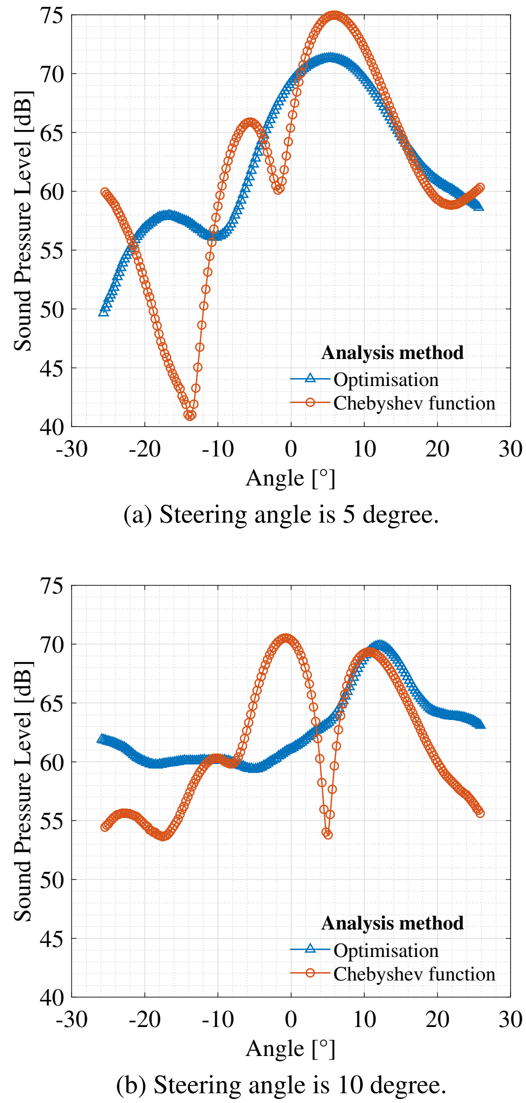

Fig. 6. Comparison of directivties between the proposed and conventional design methods for sideband frequency weights.

5. CONCLUSION

In this paper, a new weight design method for controlling the acoustic beam of parametric array loudspeakers was proposed. By optimizing the weights of the sideband frequencies by the proposed design method, the acoustic beam of the difference frequency (audible sound) can be appropriately controlled, as demonstrated by numerical analysis. Specifically, the grating lobes were suppressed by more than 10 dB compared to the conventional design method using a Chebyshev window, and the acoustic beam was formed to the target direction. In the future, we plan to study the optimal design method of the sideband frequency using the convolution model [23], and to verify it using actual equipment.

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