Beam Steering of Portable Parametric Array Loudspeaker

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***Abstract*—Portable devices such as smartphones and tablet PCs have become increasingly sophisticated and explosively spread. Opportunities for outdoor use have been consequently increasing. When the portable devices are used in public areas, personal audio system is required to avoid sound spread in the vicinity. We have already proposed the portable parametric array loudspeaker which can realize personal audio without using earphones and headphones. In this system, parametric array loudspeakers are mounted on two edges of tablet PCs and can radiate highly directional stereo sound to the user. However, the radiated sound beams may not focus on the user's ears when the user's head is moving. In this paper, we examine the phased array technique to steer the sound beam based on the user's head position. We demonstrate that the sound beam angle can be appropriately steered by using the phased array technique through experimental results.**

I. Introduction

Portable devices such as smartphones and tablet PCs have been universally used. Since the portable devices are often used in public areas, when the users want to listen to music and watch video, they have to employ earphones or headphones to enjoy personal audio in order to avoid sound spread. However, wearable sound devices such as earphones and headphones are uncomfortable and block the ambient sound that the users have to pay attention (e.g. car horn, verbal sound, and announcements). We have already proposed a method to realize personal audio by installing parametric array loudspeakers (PALs) on a portable device.

Various studies of the PAL have been carried out and their results suggests that the PAL be used to radiate a highly directional sound beam [1]-[10]. It is consequently considered that personal audio can be realized without using earphones and headphones. In addition, multiple PALs can create independent sound fields at both ears, and it is possible to realize high-precision stereophonic sound and binaural sound because crosstalk components have been greatly suppressed. However, the radiated sound beams may not focus on the user's ears due to the user's head movements.

In this paper, we apply the phased array technique to the portable PAL in order to steer the sound beam to focus on the user's ears. The experimental results demonstrate that the phased array technique can steer the sound beam appropriately.

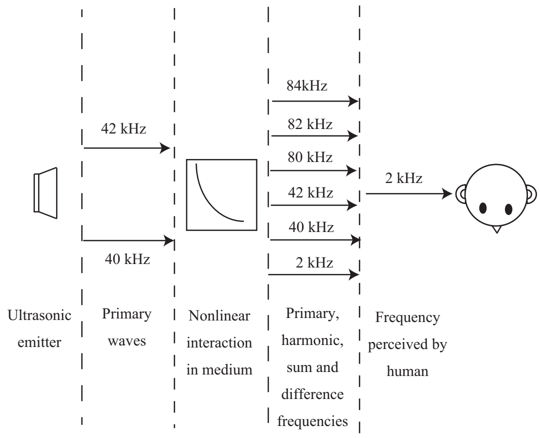

Fig. 1. Generation of primary, sum, difference, and harmonic frequency components by parametric in air.

II. Parametric Array Loudspeaker (PAL)

Figure 1 shows the principle of PAL, which is owing to the nonlinear acoustic effect. When a bi-frequency ultrasonic beam is transmitted, the difference frequency is generated as a result of the nonlinearity of air. The directivity of the difference frequency is described by an end-fire array possessing very narrow beamwidth. Similarly, when an audio signal is modulated on an ultrasonic carrier, it is recovered as the difference frequency between the sideband frequency and the carrier frequency.

III. portable PAL

Figure 2 shows a photo of the portable PAL that we have made in the laboratory. The targeted tablet is the iPad, which has a width of 240.0 mm and a height of 169.5 mm. Two independent PALs are mounted on two edges of the tablet so that they can reproduce stereophonic sound. Each PAL consists of 70 ultrasonic emitters which have a resonance frequency in the frequency band of ultrasonic waves. The ultrasonic emitters are closely arranged to increase the transmission efficiency. In addition, Fig. 3 shows the frequency response of the portable PAL. Based on the frequency response, the carrier frequency is set to 40 kHz and the lower side band amplitude modulation (LSBAM) is used as the modulation method. In the latter

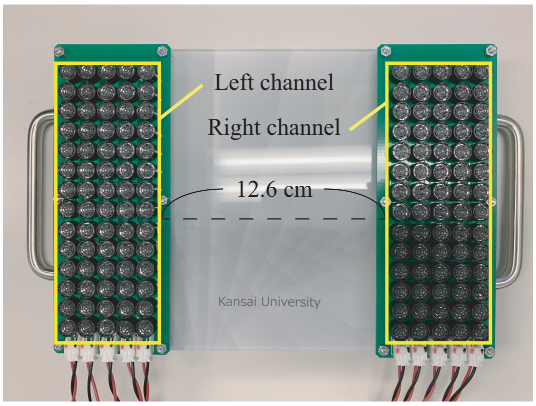

Fig. 2. A photo of the portable PAL.

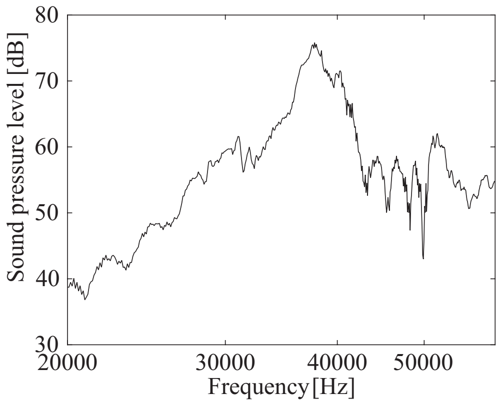

Fig. 3. Frequency response of the portable PAL.

part of this paper, the right hand side PAL is called the right channel and the left hand side PAL is called the left channel.

IV. Comparison with Ordinary Loudspeaker

In this section, we compare the directivities between the portable PAL and an ordinary loudspeaker to check whether the crosstalk components can be suppressed by the portable PAL.

A. Measurement method

The measurement environment is illustrated in Fig. 4. The equipment used for the measurement is listed in Table I, and the measurement conditions are listed in Table II. The portable PAL and the ordinary loudspeaker are rotated from $-20°$ to $20°$ at an interval of $5°$ using the turntable to measure the directivity characteristics. The radiated sound is picked up by the microphone inside the head and torso simulator (HATS). Note that MM-SPL10UBK (SANWA) was used as the ordinary loudspeaker. We separately measured left and right channels.

B. Measurement result

Figure 5 shows the directivity characteristics of the right channel in the portable PAL and the ordinary loudspeaker. In

TABLE I
Measurement equipment.

Audio interface	Fireface UC(RME)
Power amplifier	A-973(ONKYO)
Conditioning amplifier	Type 2690 0F4(B&K)
Microphone	Type 4128C(B&K)
Microphone preamlifier	Type 2669(B&K)
Turntable	Type 5960(B&K)
Turntable controller	Type 5997(B&K)

TABLE II
Measurement conditions.

Input signal	Sine wave
Sampling frequency	192 kHz
Carrier frequency	40 kHz
Fundamental frequency	2 kHz
Modulation method	DSBAM
FFT point	192000

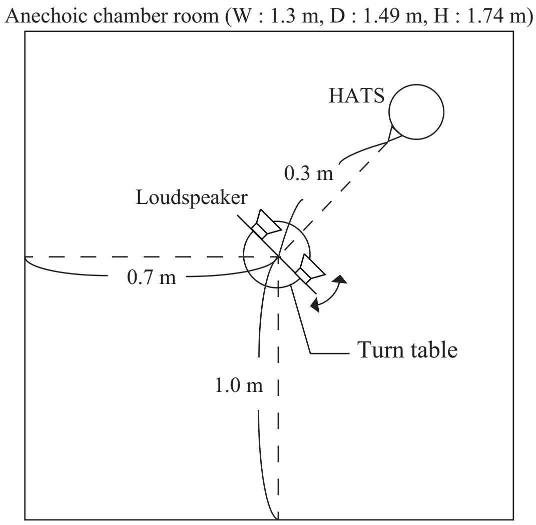

Fig. 4. Measurement environment of comparison of the directivity characteristics.

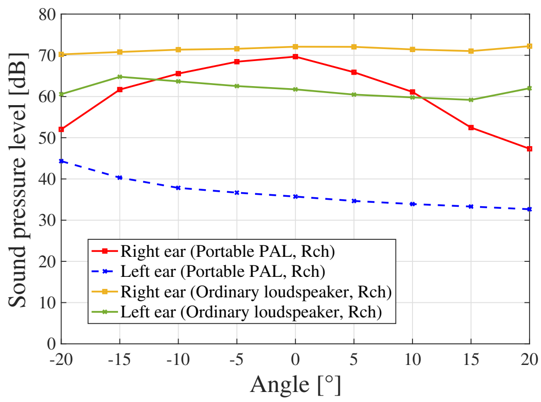

Fig. 5. Directivity characteristics of the portable PAL and the ordinary loudspeaker.

Fig. 5, the right ear is the targeted ear and the left ear receives the crosstalk, which should be reduced. It can be observed from Fig. 5 that the portable PAL has sharper directivity than the ordinary loudspeaker. Moreover, the crosstalk have been suppressed by 30 dB at 0° (the targeted direction) in the portable PAL. On the other hand, the reduction of the crosstalk is just 10 dB in the ordinary loudspeaker. From the above results, it is found that the portable PAL can generate good stereophonic sound.

V. Beam Steering

In this section, we describe beam steering for the PAL. In this paper, the phased array technique introduced in [11, 12] is used for beam steering. The phased array technique steers the demodulation wave by adjusting the phase of the modulation wave. When the input signal of each channel is delayed and weighted, the radiated angle is changed. If the delay amounts τ_1 and τ_2 are applied to the two primary frequency waves at frequencies f_1 and f_2 based on the Westervelt equation [13], the primary sound field on the propagation axis is given by

$$p_i(r, \theta = 0) = p_0 e^{-\alpha_0 r}[\cos \omega_1 (t - \tau_1 - r/c_0) + \cos \omega_2 (t - \tau_2 - r/c_0)], \tag{1}$$

where p_0 is the amplitude at the source, α_0 is the attenuation rate, r is the distance from the source to the observation point, ω_1 is the angular frequency of the lower primary frequency wave, τ_1 is the delay amount of the lower primary frequency wave, c_0 is the speed of sound, ω_2 is the angular frequency of the higher primary frequency wave, and τ_2 is the delay amount of the higher primary frequency wave, respectively.

Virtual sources for audible sound occur in the primary frequency beam due to the nonlinear acoustical interaction in air. The virtual source strength density is represented by

$$q_d = \frac{\beta p_0^2}{\rho_0^2 c_0^4} e^{-2\alpha_0 r} \frac{\partial}{\partial t} \cos \left[\omega_d (t - r/c_0) - (\omega_2 \tau_2 - \omega_1 \tau_1)\right], \tag{2}$$

where β is the nonlinearity coefficient, ρ_0 is the density of the medium, and ω_d is the angular frequency of the difference frequency wave, respectively.

If the primary frequency wave source is assumed to be circular, the difference frequency sound pressure on the axis at a distance of r can be calculated by

$$p_d(r, 0) = \frac{\beta P_0^2 a^2}{8 \rho_0 c_0^4 \alpha r} \frac{\partial^2}{\partial t^2} \cos \left[\omega_d (t - \tau_2 - r/c_0) - \omega_1 (\tau_2 - \tau_1)\right]. \tag{3}$$

It can be seen from eq. (3) that when the delay amounts for the two primary frequency waves are equal ($\tau_1 = \tau_2$), the difference frequency wave generated from the parametric array has the same delay amount.

Figure 6 shows the principle of the beamsteering for the PAL based on the phased array technique. The weight of the nth channel is denoted as w_n for $n = 0, 1, 2, \ldots, N-1$, and N is the number of channels in the ultrasonic transducer array. The delay amount for each channel is given by

$$\tau_n = n \frac{d}{c_0} \sin \theta_0, \tag{4}$$

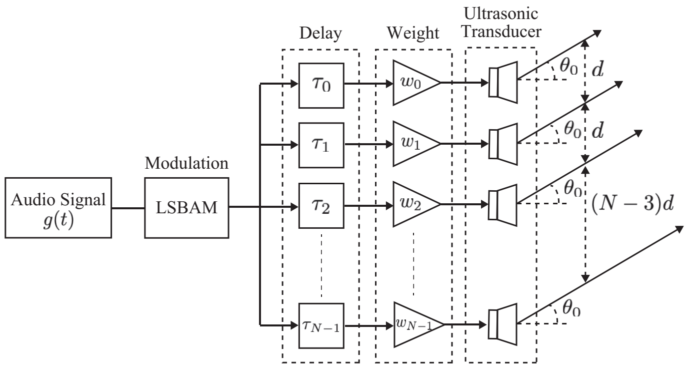

Fig. 6. Block diagram of beam steering for PAL using LSBAM based on the phased array technique.

where d is the distance between ultrasonic transducer array, and θ_0 is the steering angle. If the all weights for each channel are equal to 1 and LSBAM at the carrier frequency f_c is applied to the audio signal $g(t)$, the modulation signal for the nth channel is given by

$$S_{\mathrm{SSBAM},n}(t) = \{1 + m g(t)\} \cos(2\pi f_c (t - \tau_n)) \pm m \hat{g}(t) \sin(2\pi f_c (t - \tau_n)), \tag{5}$$

where m is the modulation index, and $\hat{g}(t)$ is the Hilbert transform of the modulated signal $g(t)$.

VI. Measurement of Beam Steering

A. Measurement method

The measurement environment is the same as Table I, the measurement conditions are shown in Table III, and the measurement environment is shown in Fig. 4, respectively. The fundamental frequency is 2 kHz and the input voltage to ultrasound emitters is set to 2.64 $\mathrm{V_{rms}}$ and 10.4 $\mathrm{V_{pp}}$. Note that the modulation method is LSBAM, the modulation index is $m = 0.8$, the number of channel is 5 on one side, and the distance between transmitters is 0.012 m.

B. Measurement result

Figure 8 shows the directivity characteristics for each steering angle (0°, 10°, and 20°). It can be seen from these results that the appropriate steering angle can be obtained, that is, the sound beam can be steered to the appropriate direction. Hence, if the user's head position could be obtained, the portable PAL with the phased array technique can send stereo sound beam to the user's ears.

VII. Conclusions

In this paper, we examined the effectiveness of the phased array technique for the portable PAL through experiments. As a result, it was found that the sound beams can be steered by using the phased array technique. Hence, if the user's head position could be obtained, the portable PAL with the phased array technique can send stereo sound beam to the user's ears. In the future, we will automatically steer the sound beams in cooperation with depth cameras such as Kinect and Intel RealSense.

TABLE III
MEASUREMENT CONDITIONS.

Input signal	Sine wave
Sampling frequency	192 kHz
Carrier frequency	40 kHz
Fundamental frequency	2 kHz
Modulation method	LSBAM
Steering angle	0, 10, 20 degrees

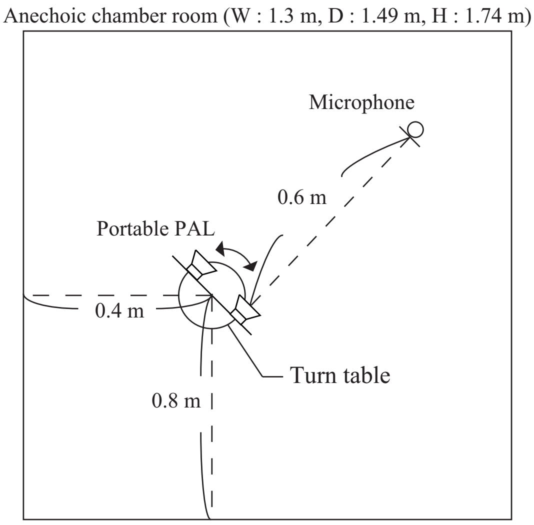

Fig. 7. Measurement environment of the directivity characteristics when the sound beam angle is steered.

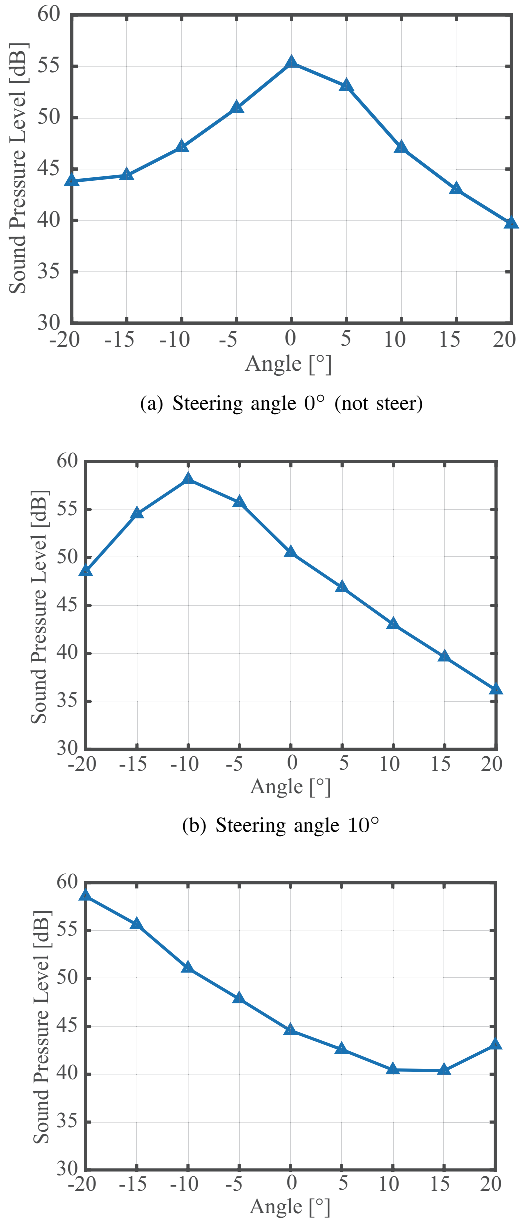

Fig. 8. Directivity characteristics when the sound beam angle is steered.

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