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Direction Control of a Parametric Speaker

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***Abstract*—In this study, we developed a parametric speaker system and analyzed the performance characteristics, wherein the direction of the audible sound wave can be electrically controlled. The system consists of an ultrasonic array transmitter with 144 ultrasonic transducer elements and field programmable gate array (FPGA) signal controllers. The phases of the amplitude-modulated signals for each transducer are controlled at 1 μs temporal resolution with ring buffers 511 μs in length. The direction can be controlled within a range of 15°, with a 2° resolution.**

Keywords—parametric, speaker, direction control, FPGA

I. Introduction

Due to their sharp directivity, parametric speakers have attracted much attention in the sound industry [1,2]. However, the direction of the speaker's sound wave is fixed, which can only be changed by mechanical control.

Some studies have proposed systems that control the direction of the audible sound wave [3-5]. Beam control is achieved by a delay-and-sum operation of the ultrasonic sound waves. However, such a system requires a large-scale circuit to obtain high resolution of the direction, because phase delay control of the signal at a short sampling rate is required. Takeoka et al. used 1-bit digital signals with sigma–delta (Σ-Δ) modulation. They demonstrated a beam steering with 2° directivity resolution and a sampling rate of 1.4 MHz [4]. However, such a system requires a higher rate of operation to obtain the same amplitude resolution with that of a multiple bit system. To overcome the limitation of delay intervals, FPGA based steerable parametric loudspeaker using a fractional delay filter was demonstrated by Wu et al. [5]. Such a system requires a large-scale circuit for the delay filter circuit. They used a system with a sampling rate of 192 kHz, and eight channels of linear array with 18 transducers.

In this paper, we demonstrate a parametric speaker system wherein the direction of the sound wave can be electrically controlled using an FPGA having ring buffers with 12-bit data as the phase-delay circuit.

II. Experimental

Parametric speakers consist of an ultrasonic transducer array, as shown in Figure 1. In this experiment, 144 ultrasonic transducer elements (Nippon Ceramic Co., Ltd. TA4010B) are arranged in a 12 × 12 elements square with a distance of 10 mm between each element. Each element has a radius of 4.3 mm, a directivity of 100° (–6 dB), and a sound pressure of 121.5 dB (SPL, input voltage 10 V_{rms}, distance 30 cm). The oscillation frequency is 40 kHz.

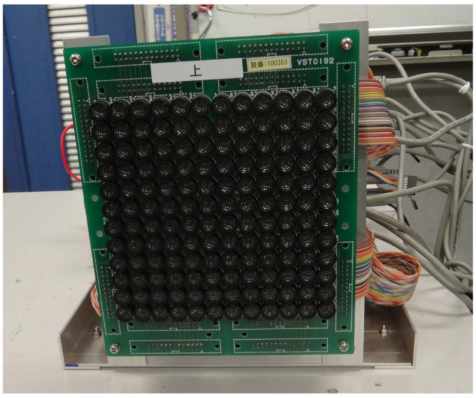


Fig. 1. Developed system.

For each element's signal, the applied signal to each transducer element is controlled by FPGA (XILINX XC6SLX150) boards with a 50 MHz system clock. Figure 2 shows a block diagram of the parametric speaker system. A sound signal is converted by an A/D converter at a sampling rate of 240 ns and a resolution of 12 bits. The signal is modulated using an ultrasonic frequency using 40 kHz amplitude modulation, which is internally generated in the FPGA at a sampling rate of 1 μs. The modulated signal is stored in a ring buffer. Time delay signals are loaded from the buffer according to the delay introduced for each transducer element. The signals are converted by D/A converters at a sampling rate of 1 μs and a resolution of 12 bits. The signals are applied to each element after amplification. The transducers are operated with a maximum input voltage of 30 V (peak to peak). The ultrasonic sound pressure is 130 dB (SPL distance 30 cm) at this voltage. The board can control 36 transducer elements; thus, four boards are used to control the 144 transducer elements. One is used as the master board and the amplitude-modulated digital signal is fed to the other three boards that are used as slave boards.

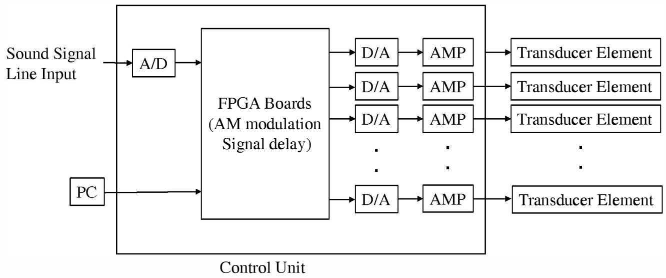


Fig. 2. Block diagram of the parametric speaker system.

In this experiment, a delay is introduced in each signal to control the direction of the parametric speaker system. The direction of the audible sound aligns with the direction of the ultrasonic sound generated by the ultrasonic transducer array. The transducer elements are located at the axis $(x_i', y_i', 0)$ on the x–y plane in the rectangular coordinate system. The distance r_i' between the position and any position $(x, y, z) = (r\sin\theta\cos\phi, r\sin\theta, r\cos\theta\cos\phi)$ in the polar coordinate system is as follows

$$r_i' = \sqrt{(r\sin\theta\cos\phi - x_i')^2 + (r\sin\phi - y_i')^2 + (r\cos\theta\cos\phi)^2}\ . \tag{1}$$

If the distance extends beyond the size of the ultrasonic array, it is calculated as follows

$$r_i' = r - x'\sin\theta\cos\phi - y'\sin\phi\ . \tag{2}$$

Therefore, the phase of the ultrasonic sound wave becomes the same in the direction (θ, ϕ), if a signal delay of

$$\Delta t_i = \frac{x'\sin\theta\cos\phi + y'\sin\phi}{v} \tag{3}$$

is introduced in each transducer element. Here, v is the ultrasonic sound velocity, θ is the horizontal direction of the sound wave, and ϕ is the vertical direction.

Since the distance between each element is 10 mm in this experiment, the maximum signal delay between each element that is necessary to obtain a horizontal directional control of 90° is

$$\Delta t_i = \frac{10\sin 90^\circ \cos 0 + 0\sin 0}{347.7} = 28.8\mu s\ . \tag{4}$$

An ultrasonic sound velocity of 347.7 m is used at a temperature of 27 °C. In the 12 × 12 element array, the required maximum time delay is $28.8\mu s \times 11 = 317\mu s$. To obtain a directional control of 90° both horizontally and vertically, the maximum time delay is $317\mu s \times \sqrt{2} = 448\mu s$. Therefore, a ring buffer with a 9-bit address is used. The sampling rate of the buffer is 1 μs, and can store data of $1\mu s \times (2^9 - 1) = 511\mu s$ .The resolution of the directional control near the front of the speaker is

$$\Delta\theta = \sin^{-1}\frac{\Delta t \cdot v}{d} = \sin^{-1}\frac{1\mu s \times 347.7\text{m/s}}{10\text{mm}} \approx 2.0\deg\ . \tag{5}$$

Nine ring buffers are used in each FPGA board to rapidly load the delayed data and to simplify the connection between the ring buffer and the signal selectors. Each ring buffer outputs four delayed signals.

The time delays (rounded off to μs) are calculated by a personal computer and are sent to the FPGA boards. The received delay data is stored in the FPGA register.

III. RESULTS

The parametric array speaker is placed at a height of 1.5 m, and sound pressure is measured by an electret capacitor microphone US-54 (Rion Co. Ltd.) at a depth z of 2, 3, 5, 7, 10, 15, and 20 m, and a horizontal length of 0–24 m at intervals of 0.5 m within a direction angle of 50°. The frequency spectrum is analyzed by an FFT analyzer.

Figure 3 shows the two-dimensional distribution of the audible sound pressure (dB) directed at θ= 0° and ϕ= 0° (no directional control). The audio signal frequency is 1 kHz. The data are interpolated, and only data within a direction angle of ±30° are plotted. A strong sound wave in front of the speaker is observed. Figure 4 shows the directivity at r=20 m. The width

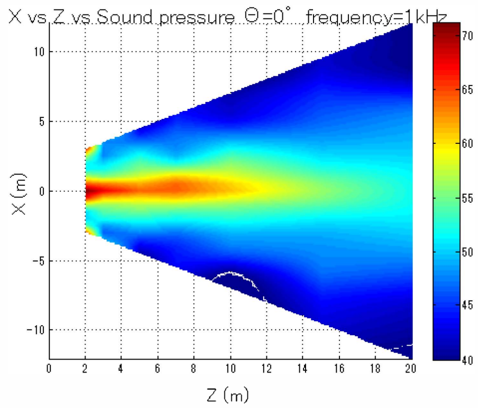


Fig. 3. Two dimensional distribution of the audible sound pressure (dB) directed at θ = 0° and ϕ = 0°. Audio signal frequency is 1 kHz.

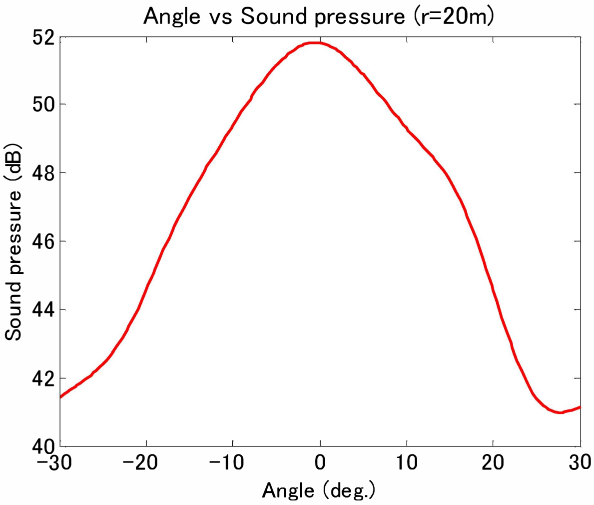


Fig. 4. Directivity of the audible sound at r=20 m. θ = 0° and ϕ = 0°. Audio signal frequency is 1 kHz.

is approximately 30° (−6 dB full width).

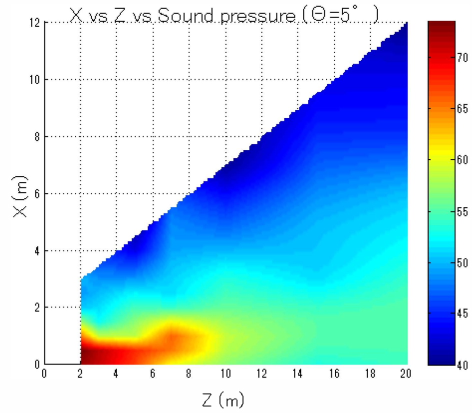
Figures 5(a)–(c) show the two-dimensional distribution of the audible sound pressure (dB) directed at θ= 5°, 10°, 20°, and ϕ= 0°. The audio signal frequency is 1 kHz. The data are interpolated, and the data inside direction angles between 0 and 30° are plotted. These results confirm that the direction of the sound wave is successfully controlled by this system.

Figures 6(a)–(c) show the directivities of the audible sound at r=20 m. The audio frequency is 1 kHz. The width is 30–40° (−6 dB full width). The width of the directivity slightly widens. Although in the case of θ= 5° and 10°, the direction of the sound wave is almost 5° and 10°, which becomes 17° at θ= 20°.

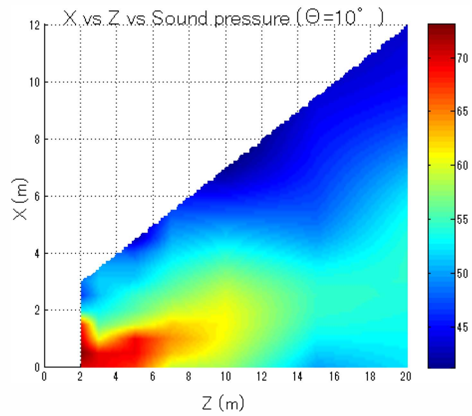
Figure 7 shows the dependence of the measured angle on the input angle, which was measured at r=5, 10, 15, and 20 m. The audio signal frequency is 1 kHz. In the range of 15°, the direction is controlled at a resolution of 2.0°. However, the measured angle becomes slightly smaller when the input angle is 20°. This characteristic appears independent of the distance r. This is because the transducer elements used in this experiment have a directivity of 100°. Even if the equiphase plane has a direction of 20°, the direction having maximum sound pressure becomes slightly smaller. The resolution is calculated using equation 3 as follows.

$$\Delta\theta \approx \frac{\Delta t \cdot v}{d \cos\theta}. \qquad (6)$$

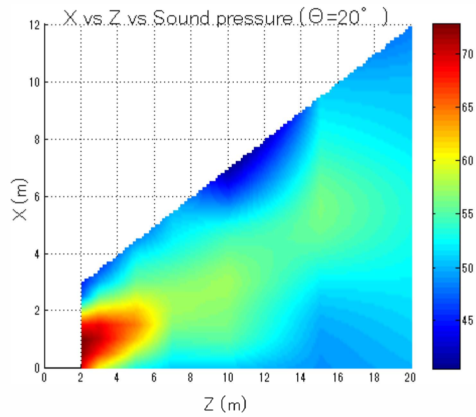
The resolution increases with an increase in the direction angle. It is approximately 2.1° for a directional angle of 20°, which exceeds the resolution calculated by the sampling rate.



(a) θ= 5°

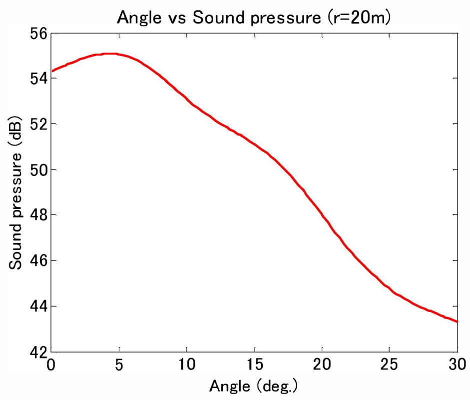


(b) θ= 10°

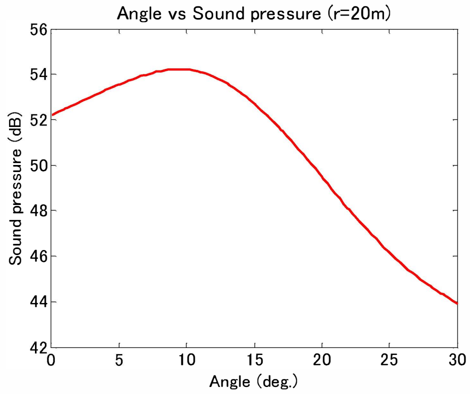


(c) θ= 20°

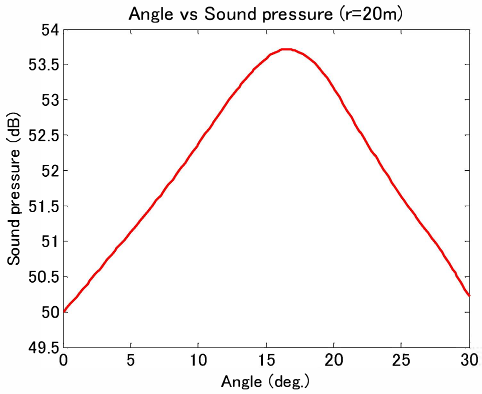
Fig. 5. Two dimensional distribution of the audible sound pressure (dB) directed at θ= 5°, 10°, 20° and ϕ= 0°. Audio signal frequency is 1 kHz.



(a) $\theta = 5°$



(b) $\theta = 10°$



(c) $\theta = 20°$

Fig. 6. Directivities of the audible sound at r=20 m. θ=5°, 10°, 20°, and $\phi = 0°$. Audio signal frequency is 1 kHz.

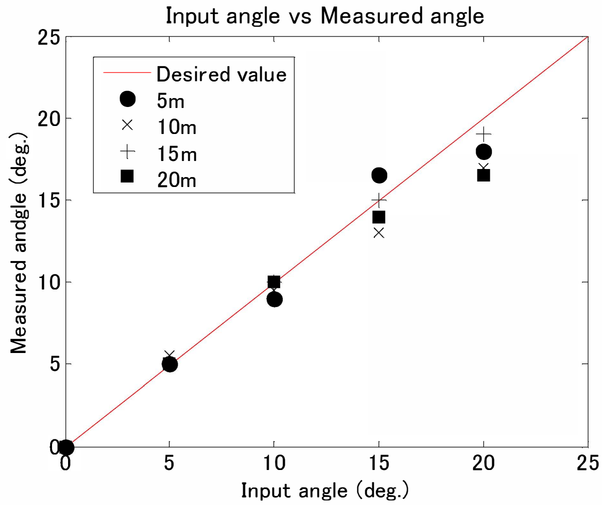


Fig. 7. Dependence of the measured angle on the input angle. r=5, 10, 15, and 20 m. Audio signal frequency is 1 kHz.

IV. Conclusions

In conclusion, we have developed a parametric speaker system and analyzed the performance characteristics, wherein the direction of the sound wave can be electrically controlled using an FPGA having ring buffers with 12-bit data. The phases of the signals for each transducer have been controlled with a temporal resolution of 1 µs with ring buffers 511 µs in length. The transducer array consists of 144 ultrasonic transducer elements (12 × 12 elements square). The direction can be controlled in the range of 15° with a 2° resolution. Control over 20° is also possible by correcting the input direction data.

References

[1] P. J. Westervelt, “Parametric acoustic array,” J. Acoust. Soc. Am., vol. 35, pp. 535-537, 1963.

[2] M. B. Bennett and D. T. Blackstock, “Parametric array in air,” J. Acoust. Soc. Am., vol. 57, pp. 562-568, 1975.

[3] W. S. Gan, J. Yang, K. S. Tan, and M. H. Er, “A digital beamsteerer for difference frequency in a parametric array,” IEEE Trans. Audio, speech and Lang. Process., vol. 14, pp. 1018-1025, 2006.

[4] S. Takeoka and Y. Yamasaki, “Acoustic projection using directivity controllable parametric loudspeaker array,” Proceedings of 20th International Congress on Acoustics, pp. 921-925, 2010.

[5] SS. Wu, M. Wu, C. Huang, “FPGA-based implementation of steerable parametric loudspeaker using fractional delay filter,” Appl. Acoustics, Vol. 73, pp. 1271-1281, 2012.