Directivity Controllable Parametric Loudspeaker using Array Control System with High Speed 1-bit Signal Processing

Shigeto Takeoka¹

¹ Faculty of Science and Technology, Shizuoka Institute of Science and Technology, Shizuoka, JAPAN

Correspondence should be addressed to Shigeto Takeoka (takeoka@ee.sist.ac.jp)

ABSTRACT

Parametric loudspeakers are known for a very sharp directivity due to their ultrasonic carrier wave. Because of this directivity, parametric speakers provide for distinguished audio applications. In this paper, an array signal processing method for parametric loudspeaker by driving transducers individually with high-speed 1-bit signal processing is introduced. We present our parametric array consisting of 576 ultrasonic transducers controlled individually, and experiments of directivity control and multi beam output are shown. By using 1-bit signal as driving signal concurrently, the signal assignments and phase control can be realized without converting or recalculation. It makes construction of the system easier in both sides of hardware and software, and the use of this speaker will be extended.

1. INTRODUCTION

The parametric loudspeaker is known to have a very sharp directivity. The emitted ultrasonic wave constructs the end fire array of demodulated sound sources because of the non-linearity of the transmission in the air. The application of the phenomenon of the nonlinear parametric array interaction to the speaker is proposed by Yoneyama et al. [1]. Since then, various researches such as the optimal modulation method and numerical computation have been proposed [2].

Recently, there are some commercial products of parametric loudspeaker made with piezo film, but array structure of ceramic transducers is used widely. Considering being array structure, application of array signal processing ought to be possible by controlling these each element. And research on directive control of a parametric loudspeaker is being performed in recent years [3, 4].

A parametric loudspeaker is called "Audio Spotlight" because of the sharpness of the directivity. Therefore, if it is possible to control the directivity arbitrarily, it is expected that the application range spreads varioulsy. However, the control points need to be arranged at intervals of less than 5 mm to emit the 40kHz signal without grating lobes. It means that over hundreds control points will be needed to construct parametric loudspeaker system with two dimensional array processing.

In this paper, an array signal processing method for parametric loudspeaker by driving transducers individually with high-speed 1-bit signal processing is introduced. We present our parametric array loudspeaker consisting of 576 ultrasonic transducers controlled individually, and experiments of directivity control and multi beam output.

2. INDIVIDUALLY CONTROLLED PARAMETRIC LOUDSPEAKER DRIVEN WITH 1-BIT SIGNAL

In high speed 1-bit signal processing, a signal is quantized with high frequency 1-bit signal as opposed to the commonly used multi-bits, and the bitstream itself includes the sound spectrum. This has an advantage in conversion with analog signal. Use of the 1-bit signal to beam forming of an ultrasonic wave signal is a method widely used in medical equipment [5], and in this paper, these are applied to a parametric loudspeaker.

2.1. 1-bit quantization of ultrasonic waves

As the quantization method for generating the 1-bit signal, delta-sigma (ΔΣ) modulation is generally used. In this method, the quantization noise is controlled by including the integrator in the feedback loop. Because the spectrum of the modulated signals that drives a parametric loudspeaker is generated around the carrier wave, the ΔΣ modulation of the band-pass type is effective. Eq.(1) shows the transfer function of the quantization noise in the 4th order ΔΣ modulator that is used in the experiments. Fig.1 shows the spectrum of the bitstream itself of the modulated 1-bit signal that entered a 40kHz sine wave that is the resonance frequency of our equipment.

\[
H_s(z) = \frac{1-1.968z^{-1} + z^{-2}}{[1-1.489z^{-1} + 0.5674][1-1.65z^{-1} + 0.7833]} \tag{1}
\]

In this modulator, the signal-to-noise ratio is kept over 100dB at 1.4MHz sampling within 35~45kHz, the range being mainly used in our experiments.
Figure 1: Spectrum of the 1-bit signal including sine wave. The spectrum other than the peak is the quantization noise.

2.2. Equipment

An important characteristic of 1-bit signal is that the converted bitstream itself includes the sound spectrum. Therefore, the 1-bit signal can be used as the driving signal of a class D amplifier. While the signal can perform digital transmission to channel assignments, the bitstream can treat as analog signals at the stage of an output. That works advantageously especially when treating the system of many channels. In this experiment, we prototyped two types of parametric loudspeakers. One is for two dimensional control and the other is for one dimensional control. The visual of equipment is shown in Fig.2 and Fig.3. The alignments of transducers of these speakers are shown in Fig.4. The 2D type is constructed with 576(24×24) independently driven transducers (576ch), and the directivity of the output beams are controlled in two dimensions by only digital delay control in FPGA. The structure of this equipment is shown in Fig.5. By using 1-bit signal, the system of the large quantity of channels is realized in compact without oversampling and “DA converter”. The 1D type is constructed with 896(64×14) transducers that are driven for each line (64ch). The structure of this equipment is shown in Fig.6. The pre-processed driving signals for each channel are loaded from a SD card. By loading each signal, this equipment is able to emit a complicated waveform. The amplitude modulation is used for the driving signal in this experiment.

Figure 2: View of the individually controlled parametric loudspeaker (2D type).

Figure 3: View of the parametric loudspeaker, each line of which is driven individually (1D type).

Figure 4: Alignments of prototyped speakers.

Figure 5: Structure of the individually delay controlled parametric transducer array with 1-bit signal.
3. EXPERIMENT OF BEAM DIRECTION CONTROL

When the element interval is set to \( d \) and acoustic velocity is set to \( c \), the relation between the delay of interelement \( (D) \) and the angle of the controlled output beam \( (\theta) \) is given as

\[
D = \frac{d \sin \theta}{c}
\]

1-bit signal processing generally has a MHz class sampling frequency, and it has no need of up-sampling for controlling directivity with enough angle-resolution by a simple delay control. Our system operates at a sampling frequency of 1.4MHz, resulting in angular resolution of approximately 2 degrees in 2D type equipment. In this chapter, the result of experiments of directivity control of the output beam by adding delay is disturbed. The directional characteristics are measured at 2m on section 3.1, 3.2, at 30cm on section 3.3 and 7.5 degrees interval in anechoic room. The G.R.A.S. 46BE is used for microphone and we analyzed 5.6MHz 1bit signal recorded by KORG MR-2000S.

3.1. Directivity control by adding delay

Experimental result about the directional characteristics of 1D type equipment is shown in Fig.7. The figure shows the level of the demodulated sound level of 4kHz sine wave. The output beam is controlled by adding delay and the controlled angle is shown in the upper right of a figure. The output beam is controlled by expected angle, but the level of the beam is decreased as the angle becomes deep.

3.2. Element interval and grating lobe

If the intervals between elements becomes more than \( \lambda/2 \) in a line array, outputs of the equal level as the mainlobe called grating lobes will occur. The angle of the grating lobe is given as

\[
\theta_N = \arcsin\left(\frac{cD + N\lambda}{d}\right) \quad (N = \pm1, \pm2, \cdots)
\]

If the element interval of the 1D type is assumed to be 5mm, the grating lobes occur in the direction of approximately 125 degrees to the mainlobe. And it means that the grating lobes are almost outside of
the output range. In Fig. 7, although some peaks have occurred, we can observe that the large grating lobe is not generated. These peaks have occurred due to the elements not being arranged in the shape of a straight line. In the case of 2D type equipment, the element interval is 10mm and the grating lobe occurs in the direction of approximately 58 degrees to the mainlobe. Fig. 8 shows the directional characteristics of the output of the 2D type equipment. The mainlobe is directed at 0 and 60 degrees. The grating lobes theoretically occur in the direction of ±58 degrees in the former, 1 and -57 degrees in the latter. And they have been observed from the experimental result in Fig. 8. Especially, the level of grating lobe that is emitted in the direction of the front is large that it cannot be disregarded.

3.3. Directivity of the transducer

The directivity characteristic of the array is decided by the product of array factor and the directivity of the element (transducer) itself. Array factor is decided by the alignment of the elements. Therefore, we measured the directivity characteristic of transducers individually with tone signal of 40kHz, and compared it with the peak level of mainlobes from the result in section 3.1. The experimental result is shown in Fig. 9. “The directivity characteristic of one transducer” shown with line is the average of the characteristics of three transducers chosen at random. The characteristic of the transducer itself corresponds to the levels of demodulated sounds.

4. MULTIPLE OUTPUT

4.1. Multiple independent beams

By adding the signals of multiple direction-controlled beams, the concurrent output of different beams is made possible. Especially at the time of driving with 1-bit signal, the driving signal can be synthesized easily without addition computation by outputting each signal with time sharing (Figure 10).

As shown in Fig. 11, we performed an experiment of concurrent multi-direction output using 3 different sound beams. Fig. 12 shows the appearance of each original signal, and the demodulated signals at 2m distance.
Figure 12: The waveform of the sound sources and the recorded sounds. (A: Violin music, B: Pop music, C: Narration)

4.2. Array output by binomial distribution

When the element is omnidirectional and the distance to the receiving point is far enough against the interval of elements, the directivity of linear array is given as

\[ f(\theta) = \sum_{n=0}^{N-1} C_n e^{j(kd \cos \theta)} \] (4)

\( N \) is the number of the elements and \( d \) is the interval of the elements.

The directivity when the array is driven by binomial distribution instead of uniform distribution output is given as

\[ f(\theta) = \sum_{n=0}^{N-1} C_n e^{j(kd \cos \theta)} \] (5)

Fig. 13 shows the distribution of amplifier for each element by uniform and binomial output.

4.3. Multiple output by binomial distribution

At the multiple outputs, by arranging the binomial distribution of each channel at certain intervals, the sidelobe can be reduced without lowering the level of each mainlobe. An example of the distribution with five channel outputs is shown in Fig. 15.

In this method, each beam is emitted by binomial distribution and from the viewpoint of total output level, the difference from uniform output becomes smaller. Fig. 16 shows the comparison of the directivity of one beam emitted by this system and by uniform distribution of 1/5. Green line of Fig. 16 shows the directivity of the beam emitted by the distribution shown by the red line in Fig. 15. Tough as shown in Figure, the sidelobe occurs depending on the lack of distribution because of the edge of
window, it is observed that the output level difference of each channel becomes small with the advantage about directivity maintained.

![Graph showing output level difference]

Figure 16: Proposed multiple beam directivity of array output.

By using 1D type equipment, we performed an experiment of three beams emitting by uniform and binomial distribution. Directional characteristics of the integrated level of ultrasonic band of three beams have been measured at 2m distance. The beams are modulated 3500, 2500, 2000Hz tone signal and those are controlled to 0, 30, -30degrees. Fig.17 shows an experimental result. It is observed that the sharpness of each beam is improved.

![Graph showing angles of directed beams]

Figure 17: Multiple beams emitted by binomial distribution.

5. CONCLUSIONS
The array processing for parametric loudspeaker with high speed 1-bit signal processing has been discussed. By using the 1-bit signal processing, maximum 576 channels controlled transducer array was achieved very simply by low power consumption. The sampling frequency of the 1-bit signal is MHz class in generally, so it allows to controlling the angle of the beams with high resolution easily and generating multiple independent audio-beams.

Furthermore, we have proposed the method of reducing the sidelobes of multiple emitted beams by arranging output distributions at certain intervals.

Because the diameter of a ceramic transducer and the wavelength of resonance frequency are closely related in generally, it is usually difficult to arrange the transducers in a linear within 1/2 interval. On the other hand, the result of the experiments in section 3.1 shows the availability of spacing transducers every 1/2, virtually by shifting to vertical direction. So the optimal arrangement of transducers for directivity control in two dimensions is the issue in the future.

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