Control of Ultrasonic Acoustic Fields by Multiple Acoustic Waveguides and Piezoelectric Transducers

－ Simulation of 2D Acoustic Fields －

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***Abstract*—We propose a system for generating and controlling an ultrasonic acoustic field using multiple acoustic waveguides and piezoelectric transducers. This system can be used as a high-power ultrasonic source for nonlinear calibration of hydrophones. In the system, ultrasonic waves are emitted from multiple transducers with controlled transmission delays, and the acoustic power is increased through acoustic waveguides before being output, this allows synthesis and control of ultrasonic acoustic fields. We simulate the proposed system as a two-dimensional acoustic field in which the computed output sound pressure determines the basic shape of the acoustic waveguide. The proposed system of five transmitting transducers and five acoustic waveguides was compared with a single transmitting transducer, and the results showed a peak sound pressure of 1.5-fold increase value at the same beam width.**

Keywords-Acoustic waveguide; Piezoelectric transducer; Ultrasonic acoustic field; Nonlinear calibration; 2D acoustic field simulation.

I. INTRODUCTION

In recent years in medicine, high-intensity focused ultrasonic fields have been used in many ways: for cancer treatment, including acoustic chemotherapy (sonodynamic therapy), for sonoporation to facilitate gene transfer, in ultrasonic elastography to image the hardness of soft tissues and organs by measuring acoustic radiation pressure, and in harmonic imaging methods that utilize harmonics for diagnosis. In industry, too, the use of high-intensity ultrasonic fields is increasing in applications such as ultrasonic cleaners and ultrasonic dispersers. In response to this growing use, the Consultative Committee for Acoustics, Ultrasonic, and Vibrations, was established in 1998 as part of the International Bureau of Weights and Measures. In addition to this, between 1999 and 2002 a pilot program of the Germany Engineering Physics Institute studied ultrasonic power, and hydrophone reception sensitivity was studied between 1999 and 2003 under a pilot program of the UK National Physical Laboratory [1]. Japan joined this effort in 2002, when the National Metrology Institute of Japan began development of measurement standards for ultrasonic.

Measurement standards for ultrasonic power of up to 15 W have been established using the acoustic balance method and standards for powers up to 100 W that use calorimetry are under development. Measurement standards for hydrophone reception sensitivity in the range 0.5–20 MHz are complete, and standards are under development for sensitivities outside of this range [1]. For ultrasonic power in particular, a source that can generate ultrasonic waves in the megahertz band at 100 W or more is needed. As ultrasonic of increasingly higher intensity is demanded in medicine, the desired acoustic fields exceed the region of linear increase, becoming nonlinear. For this reason, it is expected that nonlinear calibration and evaluation will be needed more often. Therefore, it is necessary to develop a robust hydrophone that can accommodate the spatial distribution of a powerful ultrasonic field [2], at the same time, it is necessary to develop a method to transmit high-intensity ultrasonic power.

Many previous studies have examined properties of acoustic waveguides: dispersion [3] and sound pressure profiles [4] in cylindrical waveguides, sharp bending of surface sound waves through photonic crystal waveguides [5][6], representations of acoustic waveguides with distributed transmission lines by scattering matrices [7], and ways to increase the sound pressure in a solid waveguide [8]. Additionally, one study details a patent for an ultrasonic source that can transmit ultrasonic waves along a fiber or rod [9]. Also recently, applications using acoustic waveguide are as follows: ultrasonic cleaning machine using the ultrasonic waveguide tube for reduce damage of the LSI pattern [10], structural health monitoring and nondestructive evaluation of inaccessible adhesively bonded joints using ultrasonic guided waves propagation across waveguide [11], the coiled stator ultrasound motor (CS-USM) using a closed-loop-type acoustic waveguide made from SUS304 [12], and microscopic images of tissue using a thin acoustic waveguide made from a fused quartz fiber [13].

Here, we propose a system for controlling an ultrasonic acoustic field by using multiple acoustic waveguides and piezoelectric transducers. We investigate the suitability of

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the system for use as a high power ultrasonic source by numerical simulation of a two-dimensional acoustic field.

The paper is structured in 5 sections. In Section II, we describe an overview of our proposed system. In Section III, we describe the basic conditions of 2D acoustic field simulation. In Section IV, we describe the two-dimensional model, and the simulated spatial distribution, peak acoustic pressure for our proposed system using multiple acoustic waveguides. Section V presents the conclusions and future works.

II. OVERVIEW OF THE SYSTEM

To generate high-intensity ultrasonic waves with a single transducer, it is typical to increase the power of the ultrasonic wave by applying a higher voltage to the electrodes of the piezoelectric element, but this increases the risk of deterioration or destruction of the piezoelectric element by increased temperature, such as that due to high voltage. Also, although focusing the beam of the transducer may yield the desired ultrasonic power at the focus, quantitative evaluation becomes difficult because the produced wave is no longer a plane wave. Figure 1 shows the model of the system proposed for generating high-power ultrasonic by using acoustic waveguides.

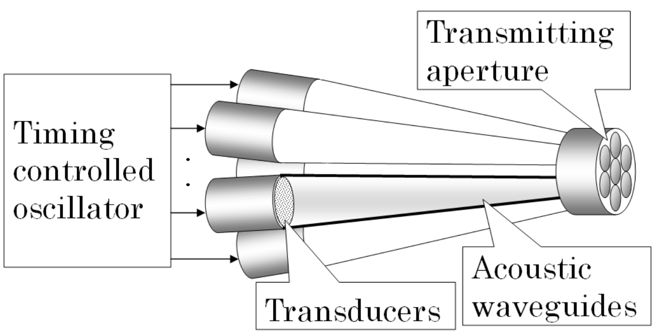

Figure 1. Ultrasonic source system using multiple acoustic waveguides and piezoelectric transducers.

After ultrasonic waves are generated by some of the transducers and the sound pressure of each ultrasonic wave is increased by the acoustic waveguides, the outputs of the ultrasonic point sources on the transmit aperture surface are formed into a beam by Huygens' principle. In this way, a high-power sound source can be constructed without increasing the output from any single transducer. However, because the beam is formed from the point sources, it is important to control the amplitude, frequency, and phase of the ultrasonic waves that are generated by each of the transducers.

III. 2D ACOUSTIC FIELD SIMULATION

The Wave2000 (Cyberlogic Inc.) package was used for simulation. Wave2000 is a two-dimensional simulator that uses the finite difference method [14], a two-dimensional displacement distribution is produced in which the relative brightness represents the magnitude of the positive and negative displacements. Because of this, the data about displacement are all magnitudes. As the basic conditions of the simulation, a transmitting ultrasonic wave is assumed at a longitudinal wave continuous frequency of 1 MHz and amplitude of 1 [a.u.]. The acoustic medium is water (temperature: 25 °C, speed of sound: 1497 m/s, acoustic characteristic impedance: 1.497 MRayl), and the wavelength of ultrasonic wave to be transmitted is 1.5 mm. Acoustic waveguides are constructed from a boundary of air (temperature: 20 °C, speed of sound: 344.0 m/s, acoustic characteristic impedance: 0.427 kRayl) that is 0.2 mm thick. To investigate the sound pressure distribution of the acoustic field, a 0.3-mm wide receiving transducer was aligned along the central axis direction or the lateral direction, and the peak–peak amplitude of the sound pressure waveform was plotted as a relative sound pressure.

A. *Sound pressure characteristics according to length of the acoustic waveguide*

In this system, it is necessary to have transmitting aperture width of 1.5 ~ 3.0 mm for beam forming. After this, following the model of Figure 2, we simulate the sound pressure at x mm away point on the center axis from the transmitting aperture plane for both transmitter and waveguide widths of d = 1.5, 2.0, 2.4, and 3.0 mm and waveguide length L mm of the acoustic waveguide.

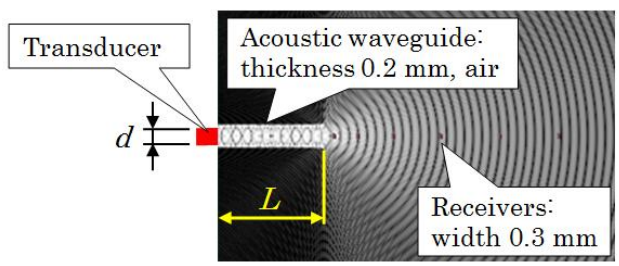

Figure 2. Model for the sound pressure characteristic using an acoustic waveguide.

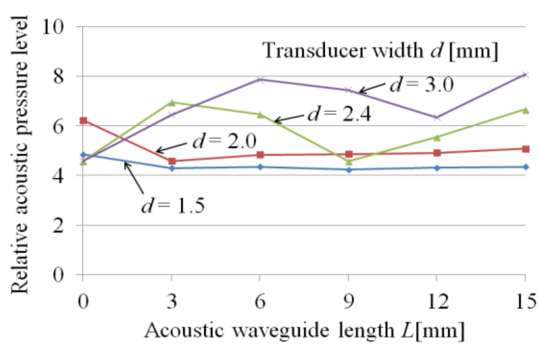

Figure 3. Sound pressure characteristic due to acoustic waveguide (x = 30 mm).

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The results at 30 mm away point are shown in Figure 3. At a transmitter width of 1.5 mm, the sound pressure becomes a constant that is independent of the length. At larger widths, it was found that the sound pressure is changed by the length.

B. Sound pressure characteristics due to bending of acoustic waveguide

To construct a system of transmitting transducers, it is necessary to bend the acoustic waveguide. As shown in Figure 4, two acoustic waveguides, each 6 mm in length, and the transmitting transducers moved from the center axis by offsets y_0 = 0.0, 0.5, 1.0, 1.5, 2.0, and 2.5 mm, simulate the sound pressure at x mm away point from the transmitting aperture plane for both transmitter and waveguide widths of d = 1.5, 2.0, and 2.4 mm.

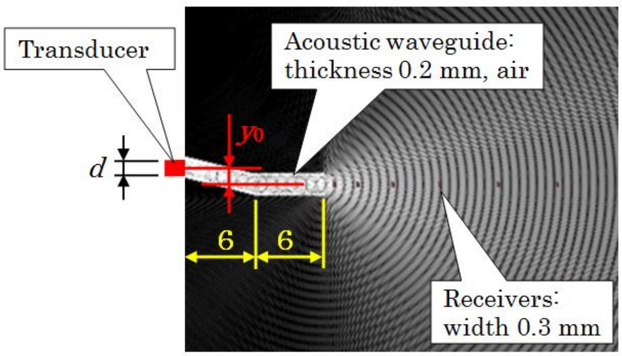


Figure 4. Model for bending acoustic waveguide.

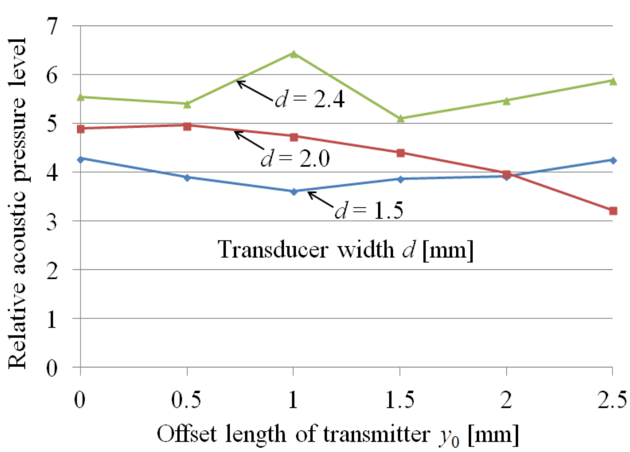


Figure 5. Sound pressure characteristics due to bending of acoustic waveguide (x = 30 mm).

The results at 30 mm away point are shown in Figure 5. When the acoustic waveguide is focused on a 1.5 mm wavelength, it is seen that bending of the acoustic waveguide is possible.

C. Sound pressure characteristics due to focusing of acoustic waveguide

Next, waves are focused by an acoustic waveguide, as shown in Figure 6, where the acoustic waveguide runs straight from the transmitting transducer (12 mm in width). The end of waveguide is connected to an acoustic waveguide 1.5 mm in width and 6 mm in length. For lengths L of the focusing acoustic waveguide in the range 30–51 mm, the sound pressures at points along the center axis from the transmitting aperture plane of the acoustic waveguide are calculated.

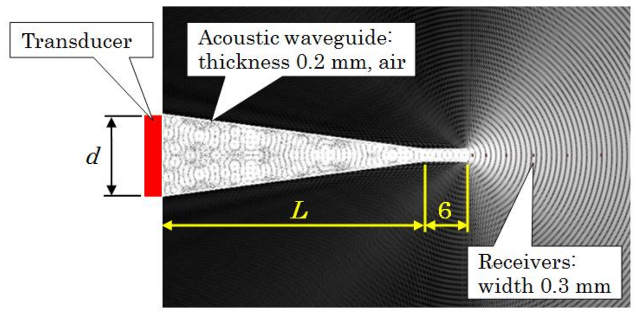


Figure 6. Model for focusing acoustic waveguide.

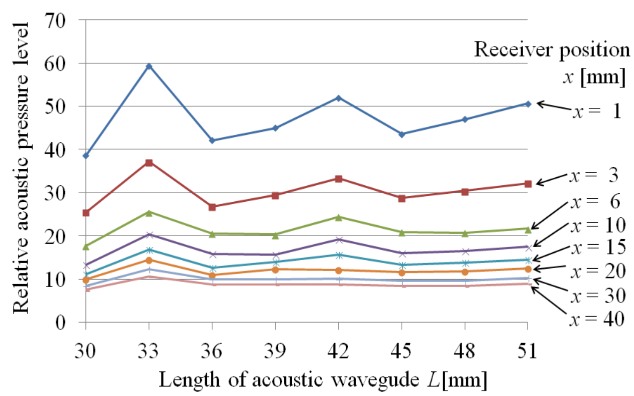


Figure 7. Sound pressure characteristics due to focusing of acoustic waveguide.

The results are shown in Figure 7. The sound pressure level is increased at 33 mm and at 42 mm.

IV. ULTRASONIC ACOUSTIC FIELDS USING MULTIPLE ACOUSTIC WAVEGUIDES

Figure 8 shows a two-dimensional simulation model of the proposed system by multiple acoustic waveguides and piezoelectric transducers. This system is composed of five transmitting transducers and five acoustic waveguides. The apertures of the acoustic waveguides vary from 12 mm to 1.5 mm along 42 mm of length to provide focus. For comparison, a single transducer must be 12 mm in width with a 2.4-mm aperture to obtain the equivalent of a 12-mm aperture arranged among the five acoustic waveguides. Because the inner and outer path lengths of each acoustic waveguide are different, the beam is formed by delaying transmission from the transducers by 0.83, 0.27, 0.00, 0.23, and 0.90 μs, this delay happens in order from the top of the system. Distances to the transmitting aperture through each acoustic waveguide from each transducer are different. Therefore, for arrival of ultrasonic waves transmitted from each transducer at the transmitting aperture of the waveguide simultaneously, each transmission delay time was adjusted.

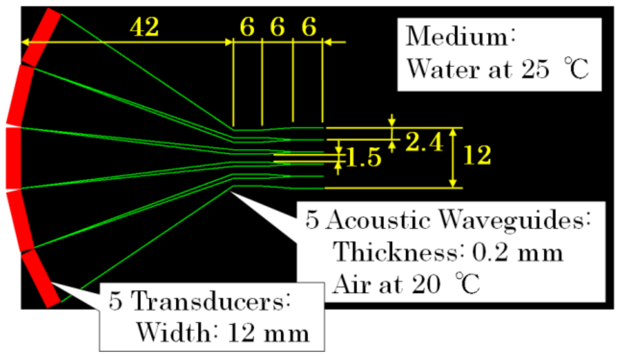


Figure 8. Two-dimensional simulation model of the proposed system.

Figure 9 shows the two-dimensional distribution of displacement by a single transducer. Figure 10 shows the same structure with the proposed system. These data show that the distribution of displacement by the single-transducer system and the proposed system are similar to each other at 60 mm away.

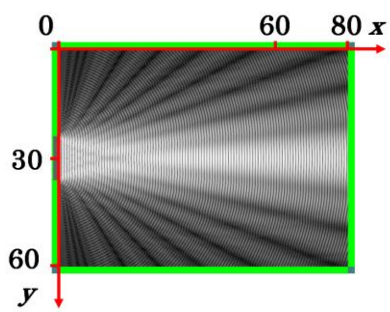


Figure 9. Spatial distribution of displacement with a single transducer (absolute value).

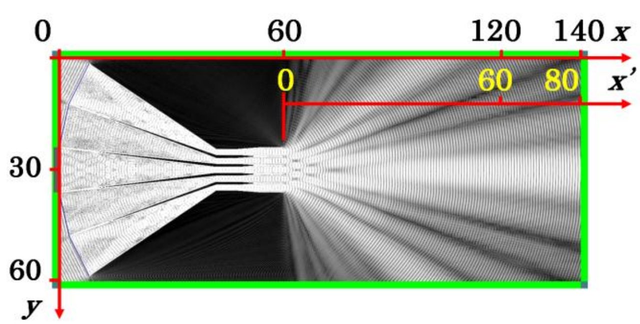


Figure 10. Spatial distribution of displacement with the proposed system (absolute value).

To quantitatively evaluate the results with the aim of determining the center pressure distributions, data from the proposed system at beyond 60 mm are overlaid with data from the single-transducer system. The results are shown in Figure 11.

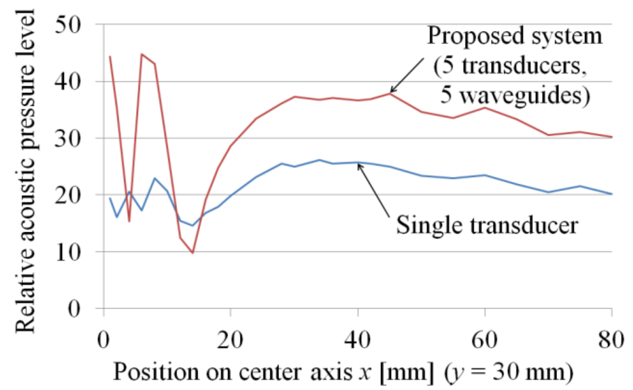
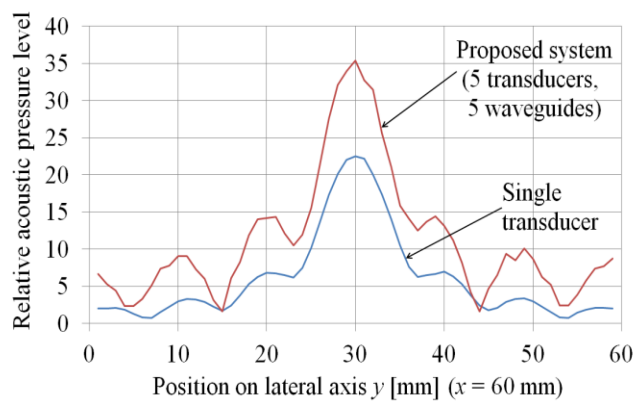
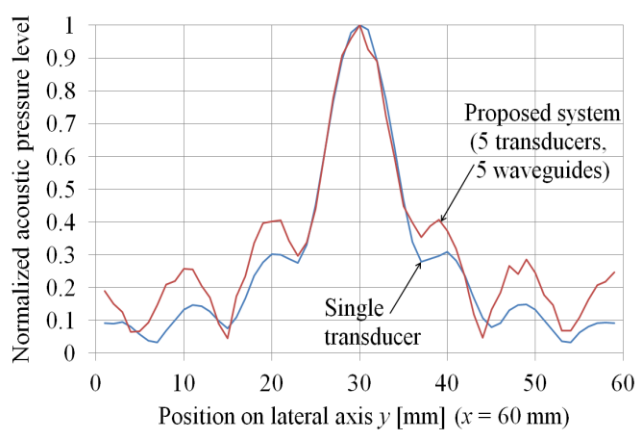


Figure 11. Comparison of the center sound pressure.



(a) Comparison of peak sound pressure.



(b) Comparison of beam width of normalized sound pressure.

Figure 12. Lateral sound pressure distribution at 60 mm on the central axis.

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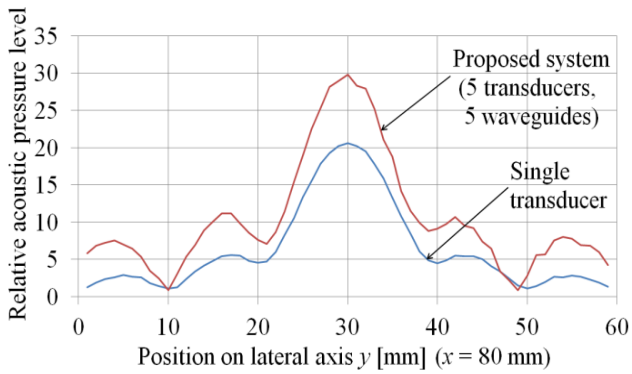
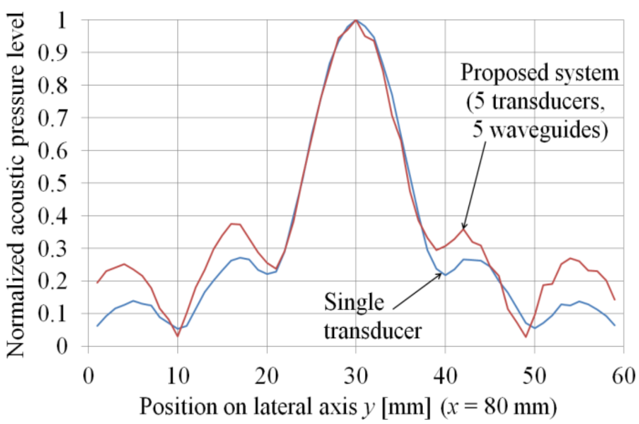


(a) Comparison of peak sound pressure.



(b) Comparison of beam width of normalized sound pressure.

Figure 13. Lateral sound pressure distribution at 80 mm on the central axis.

Next, we simulated the sound pressure distribution in the lateral direction. Figure 12 shows the results of comparison between the proposed system and a single transducer at distance 60 mm from the transmitting aperture. Figure 12 (a) can compare the peak sound pressure levels each other. Figure 12 (b) can be comparison of beam width of normalized sound pressure.Figure13 shows the results of comparison of the same, at distance 80 mm from the transmitting aperture.

TABLE I. EVALUATION OF SOUND PRESSURE DISTRIBUTION IN THE LATERAL DIRECTION

Distance x [mm]	Relative peak acoustic pressure [a.u.]	Increase factor	-6 dB beam width [mm]
60	$P_{55} = 35.34$	P_{55} / P_{10}=1.57	9.4
	$P_{10} = 22.46$		9.6
80	$P_{55} = 29.82$	P_{55} / P_{10}=1.44	12.0
	$P_{10} = 20.64$		12.2

P_{55}: 5 transducers, 5 waveguides, P_{10}: 1 transducer, non-waveguide

The results at 60 and 80 mm from the transmitting surface are analyzed for a –6 dB beam width, and the rate of increase in peak–peak sound pressure is calculated. The results are shown in Table I. An 1.5-fold (resp., 1.4-fold) increase of peak sound pressure is seen at 60 mm (resp., 80 mm), and the –6 dB beam width is almost equal between systems. But it was found from the graph of the normalized acoustic pressure level in Figures 12 and 13, that the increase factors of peak side lobe pressure are about 1.3 to 1.4.

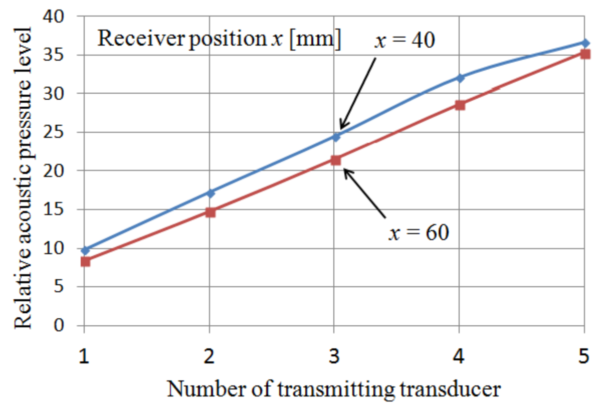


Figure 14. The relationships between maximum sound pressure levels and number of transmitting transducers.

In our proposed system, when changing the number of adjacent active transmitting transducer, we simulated the maximum sound pressure at the receiving position 40 mm and 60 mm from transmitting aperture. Results are shown in Figure 14.

V. CONCLUSIONS

We used a two-dimensional acoustic field simulation to find the basic characteristics of a high-power ultrasonic system using acoustic waveguides. The proposed system uses five acoustic waveguides instead of a single transducer, and achieved a 1.4- to 1.5-fold increase in sound pressure at the same beam width.

In the future, we will consider the shape of the acoustic waveguides further and extend the model to a three-dimensional acoustic field simulation using finite element modeling. In addition, we hope to build the probe, acoustic waveguide, and pulse generator and test the system experimentally.

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