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Sound Pressure Analysis and Experiment of Small Ultrasonic Lens

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ABSTRACT

Acoustic lens has the possibility of improvement of acoustic characteristic of transducer not only in underwater application but also medical probe. In this paper, a small acoustical lens of MHz type transducer is described. A simple 2D-FDTD calculation based on symmetry is proposed in this paper, because the 3D-FDTD of orthogonal coordinates requires large memory and long calculation time to estimate the characteristics of lens. A virtual spherical sound source whose amplitude distribution is equal to the sound propagation field of real sound source is also used for reduction of calculation. Experiments were carried out with plane-concave lens in temperature controlled water bath. Calculated results agree well with experimental results in both cases that the incident surface is plane or concave, respectively.

INTRODUCTION

Acoustical lens is often used for the ocean acoustic imaging system. The authors have reported about the characteristics of acoustic lens for underwater equipment.[1,2] Folds reported a high-resolution underwater imaging system with an acoustic lens in the sea.[3] On the other hand, ultrasonic equipment is used in not only imaging but also in therapy. For example, a high intensity focused ultrasound (HIFU)[4] is a typical application using high-power ultrasound. An acoustic lens might be useful to increase the ultrasonic power to tissue for therapy. In this paper, a small acoustic lens for an ultrasonic catheter-type probe is described. The goal of this study is to develop the designing method for an acoustic lens for a small catheter-type probe used in therapy. Although the diameter of probe must be less than 10mm in actual medical field, the lens studied is scaled up to 4 to 10 times. Many studies on focused sound fields, focused transducers, and acoustic lenses have been undertaken.[5-10] The finite-difference time-domain (FDTD) method is very useful for calculating the characteristics of sound propagation of an acoustic lens, because it can calculate multiple reflections from all objects at arbitrary points.[11,12] For precise estimation of the characteristics of an acoustic lens, a three-dimensional (3D) FDTD method is required. A common 3D-FDTD method requires a large memory and a long calculation time. To overcome these disadvantages, a simple 2D-FDTD method based on symmetry is proposed in this paper. This FDTD method with cylindrical coordinates is very useful for reducing the required resources. To improve the calculation accuracy, a virtual spherical sound source whose amplitude distribution in calculation domain equals that of actual source is also used. The sound fields of a small acoustic lens with the same physical parameters for calculation were measured in a water bath, in both cases that the incident surface is plane or concave, respectively.

CALCULATION OF ACOUSTIC FILED

2D-FDTD based on symmetry

The sound pressure field of a small acoustic lens is calculated. Figure 1 shows a calculation model of a small acoustic lens designed by optical designing software. To decrease the calculation time and memories in 3D-FDTD, a simple 2D FDTD method based on the symmetry of a cylinder is proposed. To improve the calculation accuracy, a virtual spherical sound source whose amplitude distribution in calculation domain equals that of actual source is also used. The distance between virtual sound source and the incident (first) surface of

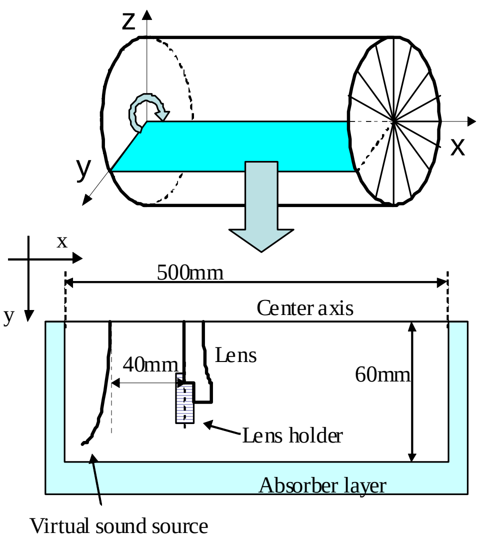

Fig.1 Calculation model of simple 2D-FDTD

lens is 40mm. It is assumed that the radius of the virtual sound source is 660mm. It is also assumed that burst-pulses of 10cycle at 2.0MHz are radiated from virtual sound source. Calculated step size Δx, Δz in analytic area are both 0.0375mm. Surfaces of the plane-concave lens are a plane and an aspherical surface as follows:

$$x(z) = \frac{z^2/(136.5)^2}{1+\sqrt{1-(1+(-0.5597))z^2/(136.5)^2}}$$

Material of lens is acrylic resin whose sound speed is 2700 m/s. Sound speed in water of 1522.2 m/s is calculated by Greenspan's equation at 37.0 degrees in Celsius.[21] Acoustic refraction index of acrylic is 0.53 at 37 deg., and theoretical focal point is 291mm from the first surface of lens.

EXPERIMENTAl SETUP

Experimental set up is shown in Fig.2 The effective diameter of lens is 40mm and is fixed by the lens holder as shown in the figure. The sound pressure distributions behind the lens are measured by a hydrophone whose diameter is 0.6mm using an automatically controlled xyz stage. The sensitivity of the hydrophone is about -253 dB *re* 1V/μPa. The incremental step size Δx, Δy, and Δz are 1mm in all directions. The temperature of the water bath is maintained constant at 37 degrees C.

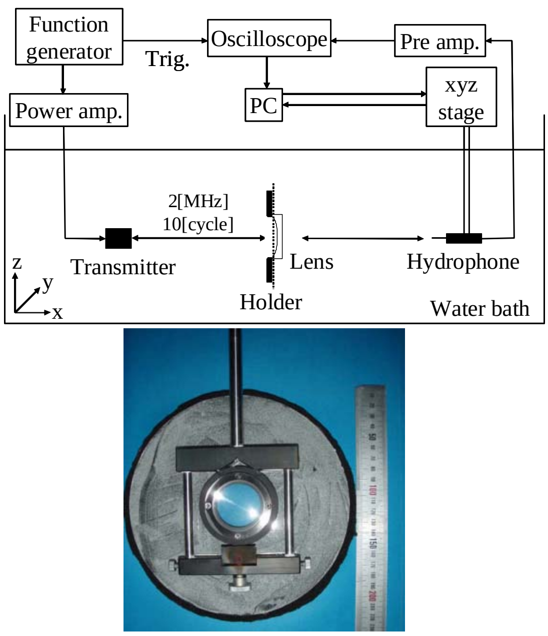

Fig.2 Experimental setup and lens holder

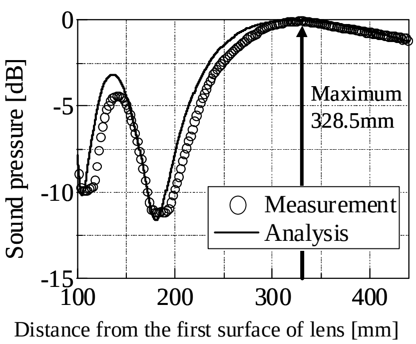

Fig.3 Sound pressure distribution on central axis

COMPARISON BETWEEN MEASUREMENT AND CALCULATION

Experiments were carried out two times. The first experiment was done when the first (left side) surface of lens was a plane. In this case, Oposide surface of lens is aspherical shape, because lens has plane-concave surface. The aspherical surface, however, is not suitable for the contact surface to the human body, if a lens system is applied to therapy. Then, the sound pressure filed was measured when the first surface of lens is an aspherical surface or contact surface is flat.

First measurement

The on-axis normalized sound pressure for measurement and analysis are shown in Fig. 3. The peak pressure is received at the point of 329mm away from the first surface of lens. The maximum convergence gain is about 10.8dB at the maximum

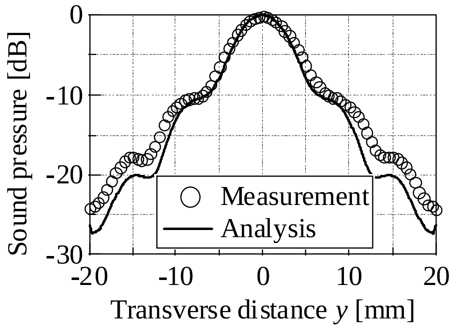

Fig.4 Transverse sound pressure at focus

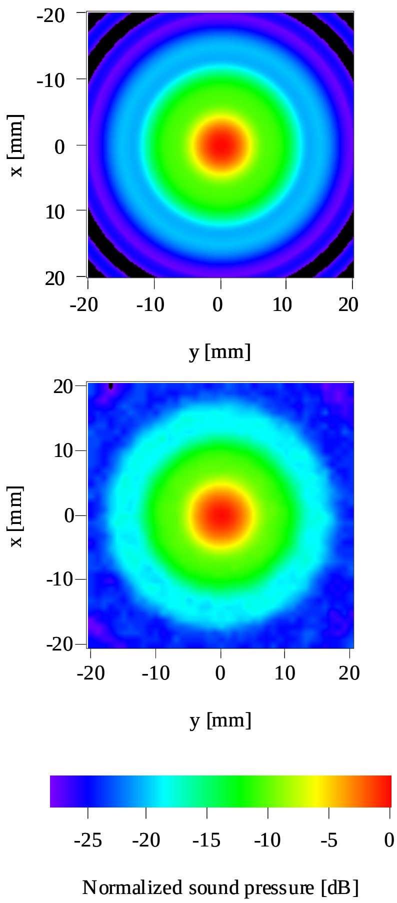

Fig.5 Transverse sound pattern at focal point:
(Top) analysis (Bottom) measurement

point. The calculated results are also normalized in the same way. It is clearly shown that the maximum and minimum points of measured data agree well with those of calculated results. This shows that the FDTD calculates the exact sound pressure field of transducer with an acoustic lens. The transverse beam patterns at the focal point are shown in Fig. 4 for measurements and calculations. The measured -3 dB beam-width is 6.5mm and is almost the same as analysis of 6 mm. The sound pressure distributions in the y–z plane are shown in Fig. 5. Calculated and measured patterns are normalized by sound pressure at the focal point. It is clearly shown that both patterns are similar. These figures show that the proposed 2D-FDTD simulation with a virtual sound source can precisely calculate the sound pressure field of an acoustic lens at normal incidence.

Second measurement

The sound pressure filed was measured when the first surface of lens is an aspherical surface against the first experiment. The on-axis sound pressures for measurement and analysis are shown in Fig. 6. The peak pressure is received at 289mm

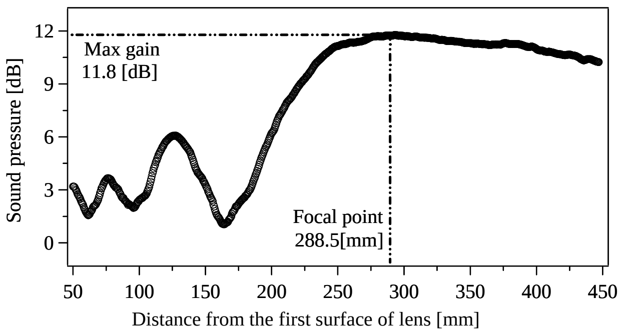

Fig.6 Sound pressure distribution on central axis in the second experiment

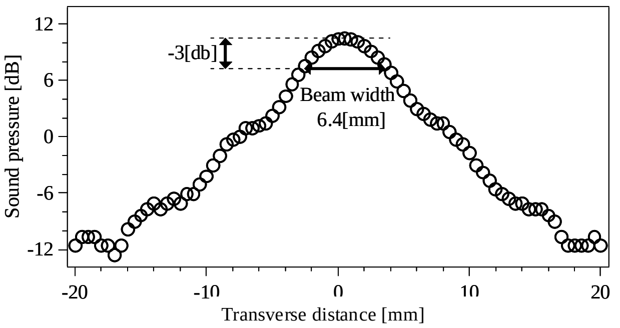

Fig.7 Transverse sound pressure at focus in the second experiment

Table1 Comparison between simulation and experiment

	#1	#2	Calculation
Focal length	329 mm	289 mm	291 mm
Beam width	6.5 mm	6.4 mm	6 mm

away from the first surface of lens. This focal length is much close to the theoretical focal point of 291mm than that in the

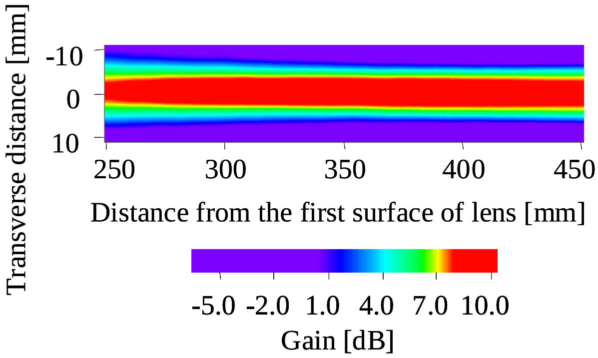

Fig.8 Sound pressure pattern in x-y plane in the second experiment

first experiment. The maximum convergence gain is also 11.8dB at the maximum point. The transverse beam patterns at the focal point are shown in Fig. 7. The measured -3 dB beam width is 6.4mm and is almost the same as analysis of 6 mm. The measured sound distribution pattern in the x–y plane is shown in Fig. 8. These results show that the proposed 2D FDTD with a virtual sound source is useful to calculate the sound pressure field of an acoustic lens at normal incidence.

CONCLUSION

The sound pressure field of a small ultrasonic probe with an acoustic lens for therapy is calculated. In order to reduce the calculation resources, a simple symmetrical 2D-FDTD method with cylindrical coordinates is proposed. A virtual spherical sound source is also used for increasing calculation accuracy. A small plane-concave lens is designed by optical software and fabricated with acrylic resin. The convergence sound field is measured in a water bath. Experiments were carried out two times. The first experiment was done when the incidence surface of lens was a plane. The aspherical surface, however, is not suitable for the contact surface to the human body, if a lens system is applied to therapy. Then, the sound pressure filed was measured when the first surface of lens is an aspherical surface. The measurement results show good agreement with calculation results by 2D-FDTD in both experiments. These results show the validity of the FDTD method. In future work, we will research incident angle dependency of convergence field.

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