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3D-Quantitative Optical Measurement of Asymmetrically Focused Ultrasound Pressure Field

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1. Introduction

High intensity focused ultrasound (HIFU) is used for the treatment of tumors such as prostate cancer. In the development of this technique, an accurate and fast measurement of the HIFU pressure field is important. A hydrophone is generally used for the measurement, but it might disturb the pressure field and scanning it in the field takes a long time. On the other hand, the optical ultrasonic field mapping (1,2) has advantages in its fastness and its nature not to interfere the acoustic field.

We succeeded in reconstructing a cylindrically symmetric ultrasound field generated by a single element transducer by using an improved optical method based on shadowgraph. (3) The cylindrical symmetry made easier to obtain the necessary accuracy of the measurement for the reconstruction.

In this study, we use basically the same method to measure and reconstruct an asymmetric ultrasound field. Much higher accuracy in the measurement than the former study (3) must be accomplished because we can no longer use the cylindrical symmetry assumption to achieve a high signal to noise ratio necessary for the real 3-D reconstruction.

2. Method

Figure 1 shows the optical measurement setup for the modified shadowgraph. The ultrasonic and optical propagation directions are defined by y and z, respectively, and the other direction is defined by x in a Cartesian coordinate. The pulsed laser was expanded by a diffusion lens and collimated by a lens in front of the water tank. The shadowgraph image formed by the light passing through the ultrasound field was taken by a charge coupled device (CCD) camera in combination with a lens in the back of the water tank. The transducer can rotate 360° around the z-axis.

It was assumed that the ultrasound pressure field forming refractive index distribution is an optical phase object that induces only phase variation. The phase variation modulates the optical intensity during propagation and forms the shadowgraph image. Figure 2 shows the relation between the optical intensity modulation and the gradient of the phase variation in the third angle projection.

I_0 and I are the optical intensities on the test section and the screen, respectively. Assuming the optical deflection angle θ due to the ultrasound pressure distribution is sufficiently small, the relation between obtained image and acoustic pressure can be shown as follows. (3,4)

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)\int p dz = -\frac{(I_{on}-I_{off})/I_{on}}{l\cdot \partial n/\partial p} \tag{1}$$

where I_{on} and I_{off} are the optical intensities on the imaging plane with and without ultrasound exposure, respectively, assuming that $I_{off} = I_0$. Note that the optical intensity difference, I_{on} - I_{off} , is divided by not I_{off} but I_{on}. This is a two-dimensional Helmholtz equation for the acoustic pressure distribution projected to the x-y plane, $\int pdz$, and can be numerically solved in a spatial frequency domain relatively easily.

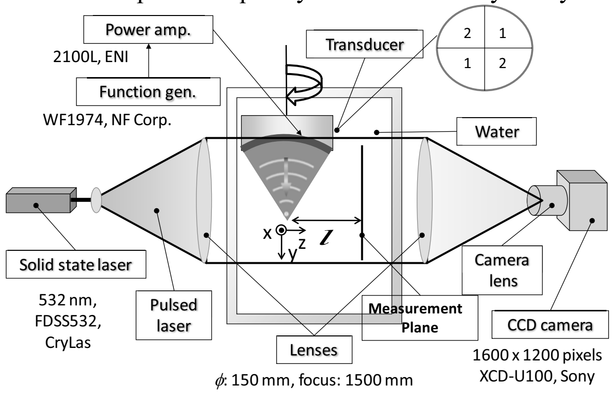

Fig. 1 Optical measurement setup

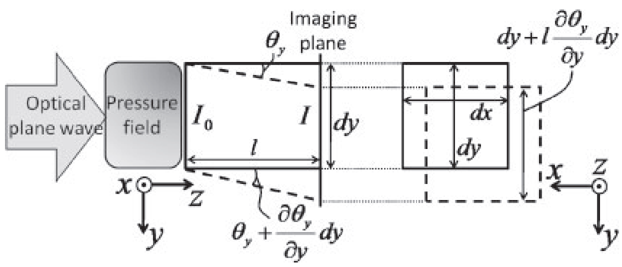

Fig.2 Intensity modulation due to phase variation in shadowgraph shown in the third angle projection.

3. Experiment

We used a transducer with four elements which were electrically combined into two pairs as shown in Fig.1.

When the two pairs are driven with opposite phases and the same amplitude, an acoustic null at the geometric focus and an asymmetric field is formed. First, 15 images with and without ultrasound exposure were acquired and averaged to reduce noise. They were used as I_{on} and I_{off} in eq. (1), respectively, and the image of $\int pdz$ on the x-y plane was obtained. 90 images were obtained every 2° for 180° on the x-z plane for 3D reconstruction of ultrasound field using CT algorithm.

For absolute acoustic pressure measurement, the optical propagation length, ℓ, was determined by measuring the depth of field of camera using a test target, and the piezo-optic coefficient, [6] $\partial n/\partial p$, was calculated to be $1.32\text{x}10^{-10}$ from the density of water of 10^3 kg/m^3, the speed of sound of 1500 m/s, the optical wavelength of 589 nm, and the refractive index of 0.134 [5] at 20℃. The result was compared with that measured by a hydrophone with an active diameter of 0.3 mm, in an acoustic pressure range from 0.6 to 1.2 MPa.

4. Result and discussion

The measured depth of field of camera resulted in the optical propagation length, ℓ, being 10–11 cm. Thus, 10.5 cm was used as the value of ℓ in the following analysis. Figures 3 and 4 show the asymmetrically focused ultrasound pressure field in the x-z plane, reconstructed from the modified shadowgraph, and that measured by the hydrophone. Good agreement is seen between the two results.

High accuracy by the proper choice of ℓ resulted in the very good agreement for the primary lobes of the asymmetrical field, which is much more complicated than a simply focused filed. There may be two potential reasons for less agreement for minor lobes. Firstly, ℓ may not have been long enough for low acoustic pressure of minor lobes. Secondly, potential discrepancy from the approximation, shown in Fig.2, at high acoustic pressure of the primary lobes may have affected minor lobes through the reconstruction CT algorithm.

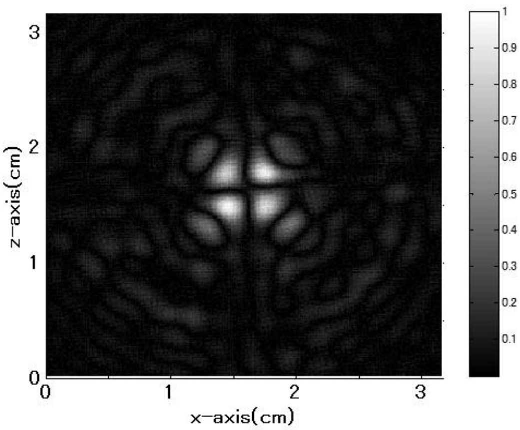

Fig.4 Asymmetrical pressure field in x-z plane reconstructed from optical measurement

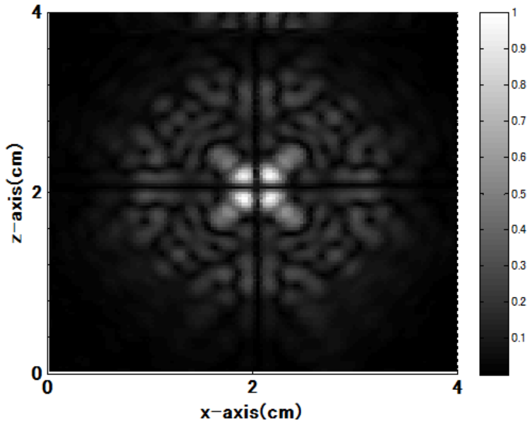

Fig.4 Asymmetrical pressure field in x-z plane measured by hydrophone

Fig.5 shows absolute ultrasound pressure by both optical and hydrophone measurement plotted against the function generator output voltage. Good agreement is seen in the plot range. Further study of this kind may clarify the disagreement seen between Figs. 3 and 4 and show the way to achieve even higher accuracy of the optical measurement.

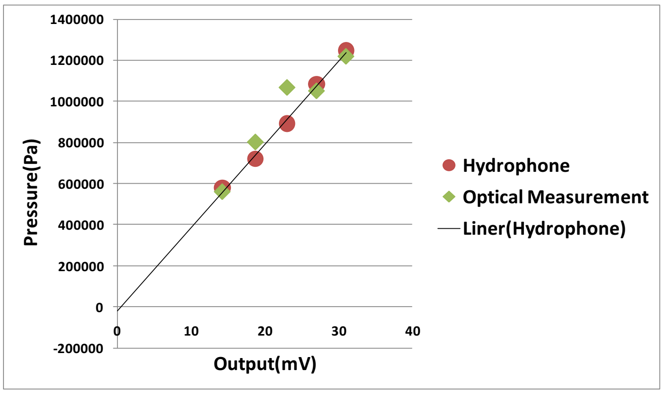

Fig.5 Compare ultrasound pressure (Hydrophone and optical measurement)

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