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Optical Phase Contrast Mapping of Highly Focused Ultrasonic Fields
集束超音波音場の位相コントラスト法による測定

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1. Introduction

HIFU (High Intensity Focused Ultrasound) is used to treat cancer such as prostate cancer. The development of this technique requires an accurate and fast measurement of the HIFU pressure field. Generally, a hydrophone is used for the measurement, but it might disturb the acoustic field and scanning it in the field takes a long time. On the other hand, the optical measurement [1] [2] does not interfere with the acoustic field and requires only a short measurement time.

In this study, we used the optical measurement setup based on a Schlieren system and developed a phase contrast method [3] by inserting an optical element called a phase plate into the Fourier plane of the Schlieren Lens. This method enabled easy capture of the projected acoustic fields, from which the pressure field could be reconstructed by a CT (Computed Tomography) algorithm [1] [4].

2. Method

Fig. 1 shows the Schlieren optical system used in this study. On the assumption that ultrasonic pressure field is an optical phase object, the light is received only phase modulation by the refractive index variation which acoustic field composes.

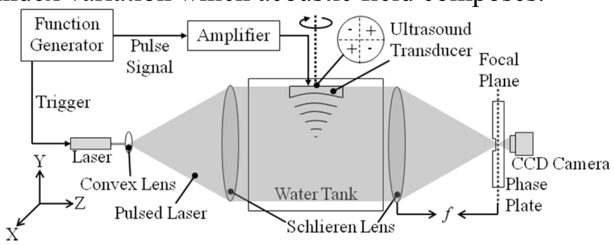

Fig. 1 Schlieren optical system

The relation between the optical phase shift and the acoustic pressure can be shown as

$$\phi = k_c \cdot \frac{\partial n}{\partial p} \int p dz \qquad (1)$$

where k_c is the optical wave number and $\partial n / \partial p$ is the piezo-optic coefficient [5] which is calculated 1.32×10^{-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 at 20°C. The acoustic pressure can be calculated by using Eq. (1) from the measured optical phase shift.

The shape of the optical wavefront on the exit from the ultrasonic field is written as follows [3].

$$t(x,y) = A\exp(j\theta_0)\exp(j\phi(x,y)) \qquad (2)$$

where A is the optical amplitude, θ_0 is the optical phase before entering the acoustic field and $\phi(x,y)$ is the optical phase shift which the ultrasonic field causes. Furthermore, when the assumption that $\phi(x,y) << 2\pi$ is used, Eq. (2) can be approximated as

$$t(x,y) \approx A\exp(j\theta_0)[1 + j\phi(x,y)]. \qquad (3)$$

The purpose of using a phase contrast method is to convert the optical phase shift, $\phi(x,y)$ into the optical intensity. This phase contrast method utilizes the property of the lens, which forms the Fourier spectrum of objects on the focal plane. The phase plate is a glass plate with a small column (200 to 500 μm in diameter) etched into its surface. The location of the column must be set to the position corresponding to the DC component of the spectrum on the Fourier plane of the Schlieren lens and its depth is such that the DC component is advanced by $\pi/2$ relative to all other components.

With the above setup, the optical intensity, $I(x,y)$ on the CCD camera can be written as

$$I(x,y) = |A[j + j\phi(x,y)]|^2 \approx A^2[1 + 2\phi(x,y)], \qquad (4)$$

assuming $\phi(x,y) << 2\pi$. We define $I(x,y) \equiv I_{on}(x,y)$, the optical intensity with ultrasonic exposure. Similarly, the optical intensity

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without ultrasonic exposure, $I_{off}(x,y)$ can be written as

$$I_{off}(x,y) = A^2. \tag{5}$$

Using Eqs. (4) and (5), the optical phase shift caused by the ultrasonic pressure field can be obtained as

$$\phi(x,y) = \frac{I_{on}(x,y) - I_{off}(x,y)}{2I_{off}(x,y)}. \tag{6}$$

3. Experiment

We used a transducer with four elements which were electrically combined into two pairs [4]. In this experiment, the two pairs were driven with opposite phases as shown in **Fig. 1** and the same amplitude.

The experimantal system consists of the above transducer (aperture and diameter: 75 mm, center frequency: 1.07 MHz), a crystal pulse laser as the light source (wave length: 532 nm, power: 4kW, FDSS 532-Q2, CryLas[GmbH]), a CCD camera (XCD-U100, SONY), a function generator (WF1974, NF), an RF amplifier (100A2, ENI), a water tank, a pair of Schlieren lenses (diameter: 150 mm, focal length: 1500 mm), a convex lens (diameter: 3mm, focal length: 6 mm), and the phase plate. The light source and the transducer were synchronously excited every 1 ms, and the shutter speed of the CCD camera was 1 ms.

First, 15 images with and without ultrasonic exposure, respectively, were acquired and averaged. They were respectively used as $I_{on}(x,y)$ and $I_{off}(x,y)$ in Eq. (6) and the image of the optical phase shift on the X-Y plane was obtained. The transducer was rotated every 2° to 180° and 90 images were obtained. These 90 distributions were used to perform the 3D reconstruction of ultrasonic pressure field applying a CT algorithm on each plane parallel to the X-Z plane. The result was compared with that measured by a hydrophone (HGL-0085, Onda) with an active diameter of 0.3 mm.

4. Result

Figs. 2 and **3** show the ultrasound pressure field in the X-Z plane, reconstructed from optical measurement and measured by a hydrophone, respectively. Good agreement is seen between the two results.

Fig. 4 shows the ultrasonic pressure along the lines going across the two negative and positive main peaks. These results also indicate the overall agreement between the optical reconstruction and the hydrophone measurement.

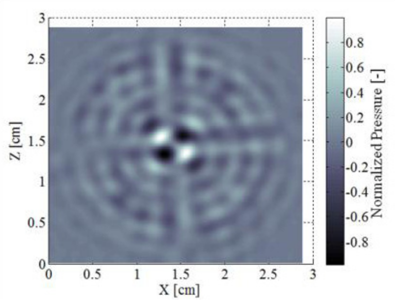

Fig. 2 Reconstruction image

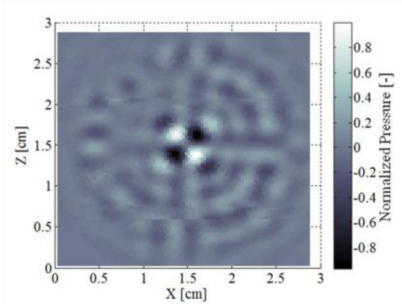

Fig. 3 Hydrophone measurement

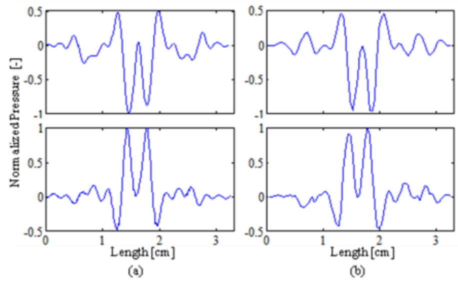

Fig. 4 Cross sections going across negative (top) and positive (bottom) main peaks of the pressure field. (a) optical reconstruction, (b) hydrophone.

5. Conclusion

We successfully reconstructed an ultrasonic pressure field from the optical images applying a phase contrast method. Further study is needed for higher acoustic pressure at which the condition of sufficiently small optical phase shift no longer holds.

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