

Quantitative Measurement of Highly Focused Ultrasound Pressure Field by Optical Shadowgraph

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Abstract. In the development of medical ultrasound techniques, fast and accurate pressure field measurement is important. The most common method to measure an ultrasound pressure field is mechanically scanning a hydrophone, which takes a long time and might disturb the acoustic field. In this study, we used an optical shadowgraph method. To perform this method quantitatively, it is important to define the optical propagation length precisely. For this purpose, a holographic diffuser was used as the imaging screen. Combined with a computed tomography (CT) algorithm, a pressure field was reconstructed, and the result was compared with that of hydrophone measurement. By using two shadowgraph data from short and long propagation lengths, the pressure field was successfully reconstructed even at a pressure level for high intensity focused ultrasound (HIFU) treatment.

1. Introduction

Accurate measurement of ultrasound field is important to ensure and improve the safety and efficacy of the medical use of ultrasound such as HIFU (High Intensity Focused Ultrasound) treatment. Fast and accurate measurement is important to quality-control, plan, and assess such treatment. The most common method to measure an ultrasound pressure field is mechanically scanning a hydrophone, which takes a long time and might disturb the acoustic field. In contrast, an optical method takes very short time and does not disturb the acoustic field.

Optical methods in previous studies [1-6] succeeded in reconstructing an ultrasound field using a computed tomography (CT) algorithm up to several hundreds kPa_{pp}. In the optical shadowgraph method, the optical propagation length between the ultrasound field, where the light receives the optical phase modulation, and the optical imaging plane is important for the accuracy. In this study, we improve this method by precisely defining the optical propagation length through setting a holographic diffuser as the imaging screen at the imaging plane. From the projections of the pressure field, obtained thereby, the three-dimensional (3D) ultrasound pressure field is reconstructed by a CT algorithm.

2. Materials and Methods

2.1 Determination of projected distribution of ultrasound pressure

The spatial change of water density due to acoustic pressure, distort the incident planar optical



wavefront to a wavy one. The light at this moment is considered to have received only phase modulation without intensity modulation. The phase variation modulates the optical intensity during propagation and forms the shadowgraph image. Figure 1 shows the optical intensity modulation in a shadowgraph [3]. The ultrasound and optical propagation directions are defined by y and z , respectively. I_0 is the optical intensity distribution of the light that has just passed through the ultrasound field, and S_0 is the area. I and S are those on the imaging plane. Assuming the optical refraction angle θ_y due to the ultrasound pressure distribution is sufficiently small, the relation between optical intensity and acoustic pressure can be written as follows.

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

Here, the geometrical optics approximation was applied. I_{on} and I_{off} are the optical intensities on the imaging plane with and without ultrasound exposure, respectively. The piezo-optic coefficient [7], $\partial n / \partial p$ for water is calculated to be $1.32 \times 10^{-10} \text{ Pa}^{-1}$ from its density of 10^3 kg/m^3 , sound speed of 1500 m/s , refractive index of 1.34 at 20°C , and the optical wavelength of 589 nm . A two-dimensional Helmholtz equation for the acoustic pressure distribution projected to the x - y plane can be solved in a spatial frequency domain.

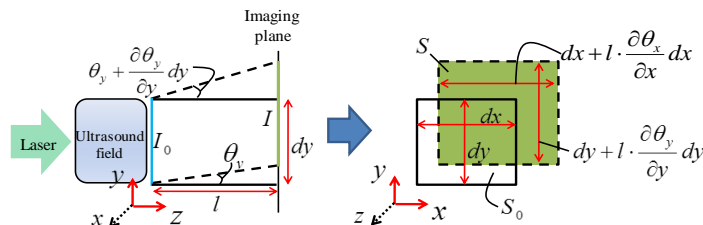


Figure 1. Intensity modulation due to phase variation.

2.2 Estimation of optical propagation length

We need to measure the optical propagation length l in eq. (1) between the imaging plane and the axis of the ultrasound pressure field. In previous study, we measured the optical depth of field and defined its center as the position of the imaging plane. However, because the depth of field is not small enough, the measurement error is relatively high when the optical propagation length l is short. To solve this problem in this study, a holographic diffuser was employed as the imaging screen to precisely define the optical propagation length.

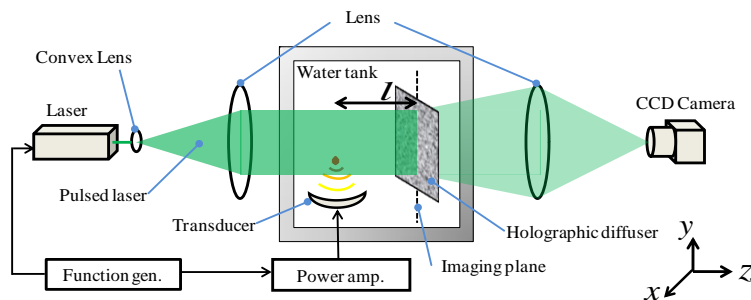


Figure 2. Optical measurement setup.

2.3 Experimental setup

The experimental setup was shown in figure 2. A solid state pulsed laser (CryLas FDSS 532-Q2, wavelength: 532 nm , pulse length: not more than 1.3 ns , power: 4 kW) was used as a light source. The light was expanded by a convex lens (diameter: 3 mm , focal length: 3 mm) and collimated by a lens (diameter: 150 mm , focal length: 1500 mm) in front of the water tank. The light having passed through the ultrasound field was converged by a lens behind the water tank. We measured the optical depth of field and set a holographic diffuser (Optical Solutions, transmittance: above 90% , diffuse angle: 5°

degree) there as the imaging screen. Here, its amplification efficiency is different at each point on the diffuser. For this reason, we moved a holographic diffuser slightly up and down in capturing an enough number images and averaged them. The shadowgraph images were taken by a CCD camera (Sony XCD-U100, 1200×1600 pixel). The laser pulse and the ultrasound from the transducer were synchronized by a function generator (NF WF 1974) exciter every 1 ms, and the shutter speed of the CCD camera was 1 ms. A lead zirconate titanate (PZT) transducer (aperture and diameter: 70 mm, center frequency: 1.14 MHz) was used to generate the ultrasound pressure field to be reconstructed. 50 images were acquired and averaged with and without ultrasound exposure, which correspond at I_{on} and I_{off} in eq. (1), respectively. The 2D Helmholtz equation in eq. (1) was numerically solved in a spatial frequency domain for $k^2(=k_x^2 + k_y^2)$, from which the 3D ultrasound pressure field was reconstructed using a CT algorithm. The 3D reconstruction of an ultrasound pressure field generally requires multiple angular projection data, obtained by rotating the transducer 180° along the y-axis. However, owing to the axial symmetry of the transducer, the projection data at only an angle was needed. We compared the reconstruction from optical measurement and the measurement by a hydrophone (Onda HGL-0085) with an active diameter of 0.085 mm. The hydrophone was scanned every 400 μm on the plane.

3. Results and Discussion

Figures 3 (a) and (b) show the normalized instantaneous pressure field of focused ultrasound generated by the symmetric transducer in the x - y plane, reconstructed from optical measurement and measured by a hydrophone, respectively. Here, the optical propagation length was 50 mm, and the peak pressure value was 3 MPa_{pp} . A short optical propagation length was chosen to measure a high pressure. To compare the two methods precisely, the data on the axial direction (x axis) and the lateral direction (y axis) are shown in figures 4 (a) and (b), respectively. In figure 4 (a), the outline from the hydrophone agree well for the main lobe with the pressure from optical measurement. However, less agreement is seen for the side lobes. In figure 4 (b), good overall agreement is seen.

To improve the S/N ratio at the side lobes in figure 4 (a), a longer propagation length was chosen and the result is shown in figure 5. Here, the amplitude was normalized based on the absolute peak pressure in figure 4 (a). With the long optical propagation length, the side lobes agree well, but the reconstruction seems to have failed in the main lobe because the assumption for eq.(1) started failing.

To solve this problem, the two sets of shadowgraph data with optical propagation lengths of 50 and 280 mm for the main lobe and side lobes, respectively, were combined. The reconstructed pressure on the axis is shown in figure 6. Good agreement can be seen for both main and side lobes. In this way, the pressure field up to 3 Mpa_{pp} was successfully measured.

In comparison to the hydrophone measurement, the absolute pressure from the optical measurement was about 50 %. Although absolute measurement should be possible by the proposed method in principle, calibration is still needed at this stage. In order to establish an absolute pressure measurement method, we have to solve this problem.

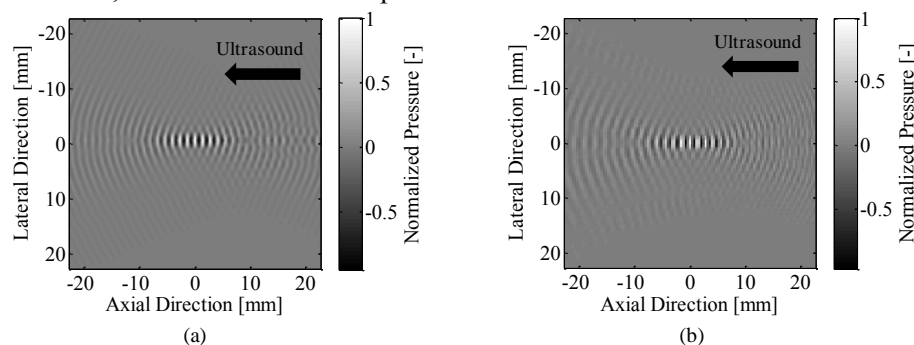


Figure 3. Normalized absolute pressure field (a) optical and (b) hydrophone measurement.

4. Conclusions

We reconstructed an ultrasound pressure field from background-subtracted shadowgraphs. Using a holographic diffuser, the optical propagation length was precisely defined. Using two sets of shadowgraphs with optimal optical propagation lengths, we successfully reconstructed an ultrasound pressure field identical to hydrophone measurement up to 3 MPa_{pp}. Some problem is still remaining, which must be solved to establish an absolute pressure measurement method.

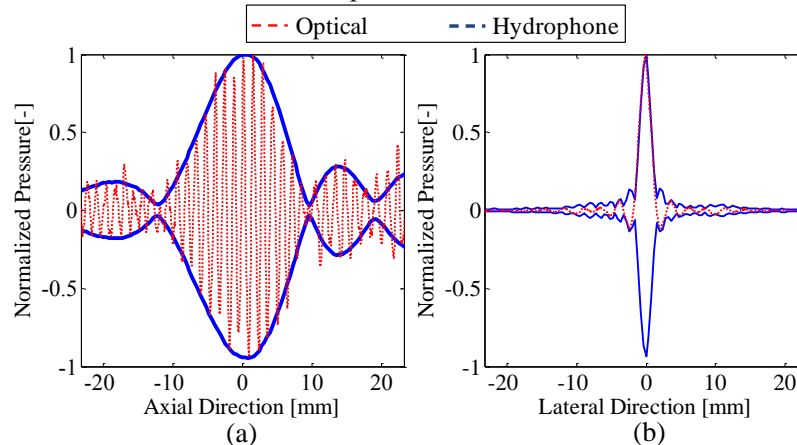


Figure 4. Comparison between two methods for $l=50$ mm. (a) axial and (b) lateral direction.

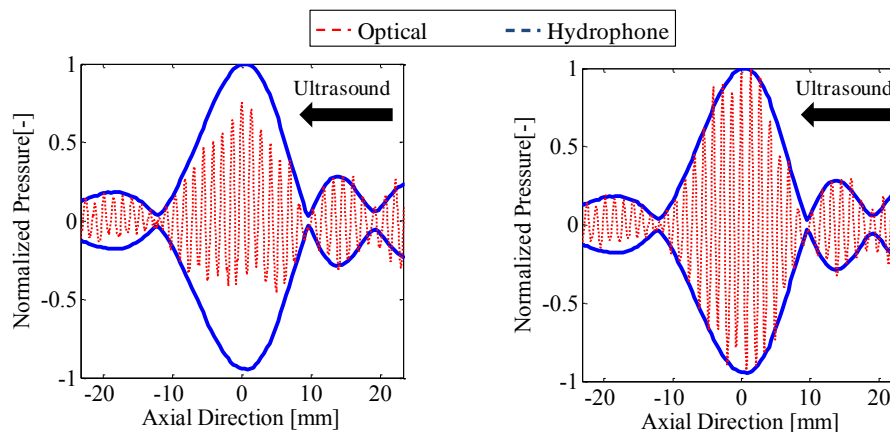


Figure 5. Comparison between two methods for $l=280$ mm.

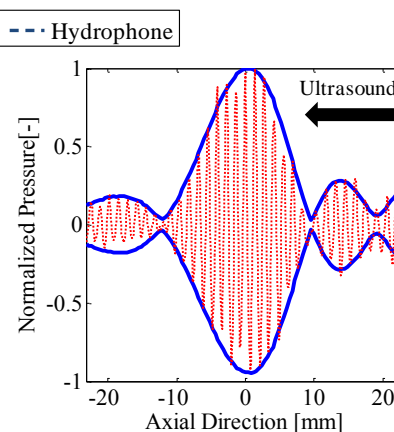


Figure 6. Comparison between two methods for the combined data.

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