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Quantitative Measurement of Ultrasound Pressure Field by Optical Phase Contrast Method and Acoustic Holography

光位相コントラスト法と音響ホログラフィ的解析による超音波音場の定量測定

Seiji Oyama†, Jun Yasuda, Hiroki Hanayama, Shin Yoshizawa, and Shin-ichiro Umemura (Tohoku Univ.)
大山 誠司†，安田 惇，花山 洋貴，吉澤 晋，梅村 晋一郎(東北大学)

1. Introduction

Fast and accurate measurement of ultrasound pressure field accelerates the development of ultrasonic intruments for medical application. The most common method to measure ultrasound pressure field is a hydrophone scan which requires a long scanning time and may disturb the acoustic field. In this study, we proposed an optical phase contrast method[1-3] enabling a fast and noninterfering measurement.

This method measures the modulated phase of light caused by the ultrasound pressure field. Then, a computed tomography (CT) algorithm[1][3] is applied to reconstruct the 3D ultrasound pressure field and measure the pressure field quantitatively. At higher ultrasound intensity, however, the problem is that the modulated optical phase in focus is wrapped[3].

This study proposes an approach that combines the optical phase contrast method and acoustic holography[4] to quantitatively eveluate a focused ultrasound pressure field at high intensity. At first, the optical measurement of focused ultrasound was performed over the field near the transducer. Second, nonlinear propagation of the measured ultrasound was simulated.

2. Methods

2.1 Theory of Optical phase contrast method

Fig. 1 shows optical phase contrast measurement setup used in this study. The ultrasound propagation in water created a medium of density gradient with varied refractive index which then modulated the incident optical phase. The relation between the modulated optical phase and the acoustic pressure can be shown as

$$\phi = k_c \cdot \frac{\partial n}{\partial p} \int p dz \tag{1}$$

where k_c is the light wave number, $\partial n/\partial p$ is the piezo-optic coefficient[5] calculated as 1.32×10^{-10} Pa^{-1} from the water density of 10^3 kg/m^3, the sound speed of 1500 m/s, the light wavelength of 589 nm, and the refractive index of 0.134 at 20°C.

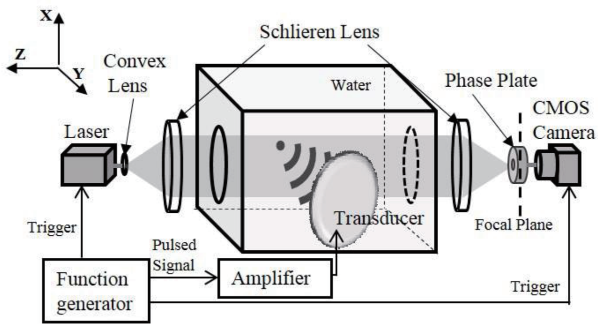

Fig.1 Optical phase contrast measurement setup

In **Fig. 1**, the Schlieren lens forms the Fourier spectrum of the ultrasound pressure field on the focal plane, which consists of the DC component and diffracted light component. A phase plate with two small columns (100 μm in diameter) etched into its surface is then setup at the focal plane so that only the DC component could pass through one of the columns. Their thickness was chosen so that the phase of the DC component is advanced by π/2 and 3π/2. The optical intensity obtained using each column is defined as I_{on+} and I_{on-}, respectively. Then, the optical intensity modulation can be written as

$$\begin{aligned} I_{on+}(x,y) &= \left|A\exp(j\phi(x,y)) - \alpha + \alpha\exp\{j(\pi/2)\}\right|^2 \\ &= A^2 + 2\alpha^2 - 2A\alpha\{\cos\phi(x,y) - \sin\phi(x,y)\} \end{aligned} \tag{3}$$

$$I_{on-}(x,y) = A^2 + 2\alpha^2 - 2A\alpha\{\cos\phi(x,y) + \sin\phi(x,y)\} \tag{4}$$

where A is the optical amplitude, $\phi(x,y)$ is the optical phase modulated by the ultrasound field, and α^2 shows the decreased intensity of the DC spectrum. The optical intensity in the absence of ultrasound can be shown as

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

Using Eq. (3)-(5), the modulated optical phase can be written as follows

$$\sin\phi = \frac{I_{on+} - I_{off+}}{4A\alpha} - \frac{I_{on-} - I_{off-}}{4A\alpha} \tag{6}$$

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s.oyama@ecei.tohoku.ac.jp

$$\cos\phi = \frac{\alpha}{A} - \frac{I_{on+} - I_{off+}}{4A\alpha} - \frac{I_{on-} - I_{off-}}{4A\alpha} \quad (7)$$

2.2 Acoustic holography

Acoustic propagation was simulated in this study based on by the Rayleigh integral, including the effects of nonlinearity and absorption in the focused ultrasound. The nonlinear model used in this study can be written as follows

$$p = A\left\{\left(\frac{\Delta\rho}{\rho_0}\right) + \frac{1}{2}\frac{B}{A}\left(\frac{\Delta\rho}{\rho_0}\right)^2\right\} \quad (8)$$

where ρ is the density and A/B is the acoustic nonlinear parameter. Values in water at room temperature as ρ_0 = 1000 kg/m^3, A = 2.25·10^9 kg/m·s^2, and B/A = 5.0, in addition to the same parameters in (1). The result from the optical measurement was used as a planar sound source.

3. Experiment

The pulsed laser (wavelength: 532 nm, SPOT-10-200-532, ELFORLIGHT) was expanded by a convex lens (Φ: 3 mm, f: 6 mm). It was then collimated and converged by two Schlieren lens (Φ: 150 mm, f: 1500 mm) located at the sides of the water tank. The light was then captured by a CMOS camera (ORCA-Flash2.8, Hamamatsu Photonics K.K.). Its depth of field was measured beforehand, and an axisymmetric PZT transducer (Φ: 72 mm, f: 72 mm, center frequency: 1.14 MHz) was placed there. The laser pulse, the camera and the ultrasound signal were synchronized by a function generator (NF WF1974) every 50 ms. The shutter speed of the CMOS camera was 1 ms.

The voltage driving the transducer was set to 81.7 V_{pp}. 150 images with and without ultrasonic exposure were captured and averaged for each case. Using Eq. (6), (7), the modulated phase was calculated. The ultrasound pressure field near the transducer was reconstructed using a CT algorithm. The nonlinear acoustic field was obtained by the simulation using the pressure field data. The result was compared with the measurement by a hydrophone.

4. Result and Discussion

Fig. 2 shows the optically measured ultrasound pressure field in the lateral direction between the transducer and the focus. Nonlinear acoustic propagation was simulated using this data. **Fig. 3** shows the simulated ultrasound pressure field. The result from the optical-measurement based acoustic holography are compared directly against the independent hydrophone measurement as shown in **Fig. 4**. Good agreement is seen for both main and side lobes. This combined method was able to measure the pressure field up to 5.5 MPa_{pp}. The difference in the absolute pressure between the combined method and hydrophone measurement was about 15 %.

4. Conclusion

A new approach that combines an optical phase contrast method and acoustic holography provided good agreement with hydrophone measurement even at high ultrasound intensity. Further study is needed for the measurement of high-intensity focused ultrasound at a therapeutic level (10MPa_{pp}~).

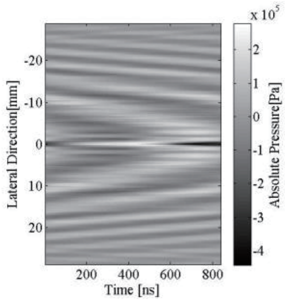

Fig. 2 Ultrasound pressure field near the transducer.

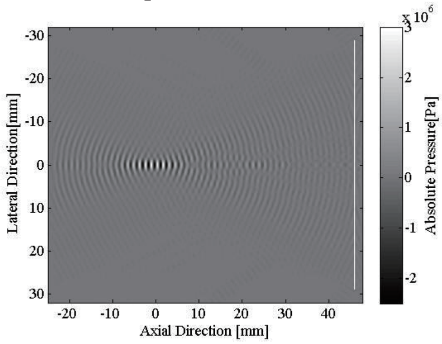

Fig. 3 Ultrasound pressure field reconstructed from optical-measurement based acoustic holography.

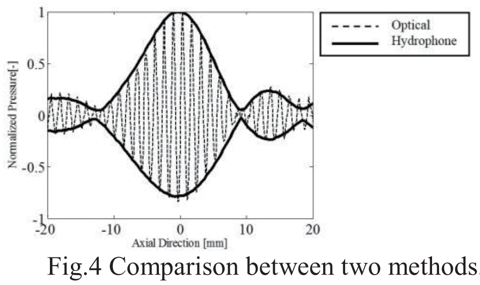

Fig.4 Comparison between two methods.

References

1. T. A. Pitts, A. Sagers, and J. F. Greenleaf: IEEE Trans. Ultrason., Ferroelect., Freq. Contr. **48** (2001) 1686.
2. H. Ouchi, N. Kudo, K. Yamamoto, and H. Sekimizu: Technical report of IEICE **19** (2004) 9.
3. S. Harigane, R. Miyasaka, S. Yoshizawa and S. Umemura: Jpn. J. Appl. Phys. **52**,(2013) 07HF07.
4. W. Kreider, P. V. Yuldashev, O. A Sapozhnikov, N. Farr, A. partanen,M. R.Bailey, and V. A. Khokhlove: IEEE. Trans. Ultrason., Ferroelect., Freq. Contr. 60 (2013) 1683.
5. M. J. Crocker: Encycl. Accoust. **1** (1997) 1