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Quantitative Measurement of High Intensity Focused Ultrasound Pressure Field by Optical Phase Contrast Method Applying Non-Continuous Phase Unwrapping Algorithm
光位相コントラスト法に位相アンラップ法を適用した高強度集束超音波音場の定量測定

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1. Introduction

Fast and accurate measurement of ultrasound pressure field leads to the enhancement of safety and efficacy of ultrasound application in therapeutic especially HIFU (High Intensity Focused Ultrasound) therapy. For this purpose, we proposed a new method using optical phase contrast method [1,2], which takes very short time and does not disturb the acoustic field in contrast to the mechanically scanned hydrophone method.

This method measures the modulated phase of light cause by the ultrasound pressure. Then, a computed tomography (CT) algorithm[1,2] was applied to reconstruct the ultrasound pressure field. We have already succeeded in the reconstruction at low ultrasound intensities. At high intensity, however, the modulated phase value surpasses π, causing the phase data to be wrapped. In this study, we introduce a non-continuous phase unwrapping algorithm to solve this problem and quantitatively measure the ultrasound pressure field at high intensity.

2. Method

Fig. 1 shows the modified Schlieren setup used in this study. The ultrasound propagation in water caused the spatial change in water density, resulting in a slight change in the refractive index which then modulates the phase of the incident light. The relation of the modulated optical phase and the acoustic pressure can be written as

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

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

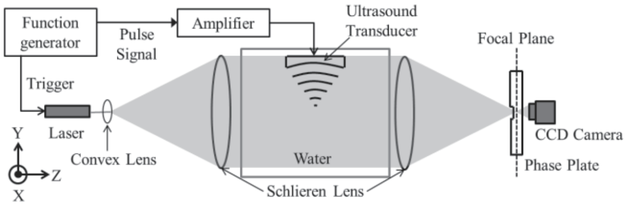

Fig. 1 Schlieren optical setup

The light wavefront that just passed the ultrasound medium can be described as follows[1)]

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

where A is the optical amplitude and $\phi(x,y)$ is the modulated optical phase. The main role of the proposed method is that it converts the optical phase modulation into intensity modulation. In Fig. 1, the Schlieren lens form Fourier spectrum of ultrasound pressure field on the focal plane, which consists of DC component and diffraction component.

A phase plate with two small columns (100~200 μm in diameter) etched into its surface is then setup at the focal plane so that only DC component could pass through one of the columns. Their thickness was chosen so that the phase of DC component is advanced by $\pi/2$ and $3\pi/2$. The optical intensity obtained using each column are defined as $I_{\mathrm{on+}}$ and $I_{\mathrm{on-}}$ respectively. Then, the intensity modulation can be written as

$$I_{on+}(x,y) = \left| A\{\exp(j\phi(x,y)) - 1\} + A\exp\{j(\pi/2)\} \right|^2$$
$$= A^2(3 - 2\cos\phi(x,y) + 2\sin\phi(x,y)) \qquad (3)$$

$$I_{on-}(x,y) = A^2(3 - 2\cos\phi(x,y) - 2\sin\phi(x,y)) \qquad (4)$$

The optical intensity in the absence of ultrasound can be written as

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

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

$$\sin\phi = \frac{I_{on+} - I_{off+}}{4I_{off+}} - \frac{I_{on-} - I_{off-}}{4I_{off-}} \qquad (6)$$

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$$\cos\phi = 1 - \frac{I_{on+} - I_{off+}}{4I_{off+}} - \frac{I_{on-} - I_{off-}}{4I_{off-}} \qquad (7)$$

The unwrapping algorithm used in this study is based on the non-continuous reliability-guided path algorithm[3,4]. In a 3×3 window, the second difference of horizontal $H(i,j)$, vertical $V(i,j)$ and diagonal $D_1(i,j)$, $D_2(i,j)$ is calculated using [3, Eq. (1)]. The pixel reliability value R at the point (i,j) is

$$R(i,j) = 1\Big/\left|H^2(i,j) + V^2(i,j) + D_1^{\,2}(i,j) + D_2^{\,2}(i,j)\right| \qquad (8)$$

The unwrapping path follows the edge reliability value that is sorted in descending order, which is defined as the summation of pixel reliability value between two neighboring pixels.

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 CCD camera (XCD-U100, SONY). Its depth of field was measured beforehand and an axisymmetric PZT transducer (Φ: 70 mm, f: 70 mm, center frequency: 1.14 MHz) was placed there. The laser pulse and the ultrasound signal were synchronized by a function generator (NF WF1974) every 1 ms. The shutter speed of the CCD camera was 1 ms.

The voltage driving the transducer was set to 1.5 and 80.5 V_{pp}. 220 images with and without ultrasonic exposure were captured and averaged for each case. The decrease in DC component intensity, A, at high ultrasound intensity was also measured and taken into account. Using Eq. (6), (7), the modulated phase was calculated at each ultrasound intensity. The modulated phase at the low intensity was then deliberately folded by 54 times linearly and wrapped for comparison. Then, the phase unwrapping process was conducted on both phase data and the unwrapped results were compared and assessed. A CT algorithm was applied to the cross-sectional unwrapped data and the pressure field was reconstructed.

4. Result and Discussion

Fig. 2 (a) shows the distribution of the linearly folded phase from the measurement at the low ultrasound intensity. This data was successfully unwrapped as shown in **Fig. 3 (a)**. **Fig. 2 (b)** shows the phase distribution measured at the high ultrasound intensity. This data was mostly unwrapped properly as in **Fig. 3 (b)** except for some parts. The resulting reconstructed ultrasound pressure distribution in **Fig. 4 (b)** shows many small corrugations, unseen in **Fig. 4 (a)**.

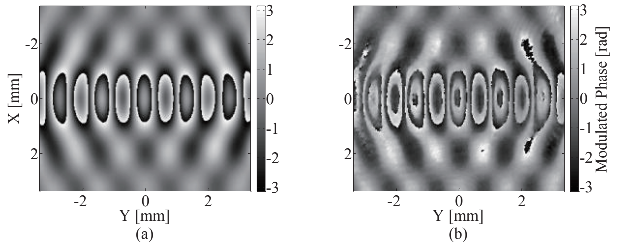

Fig. 2 Modulated phase image of (a) linearly folded phase data and (b) real phase data

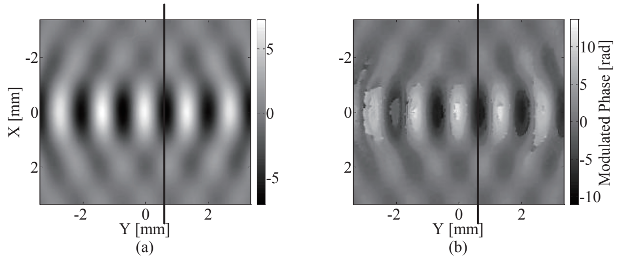

Fig. 3 Unwrapped phase image of (a) linearly folded phase data and (b) real phase data

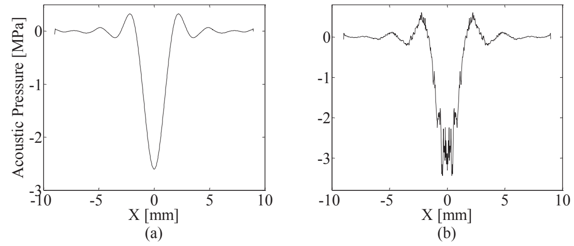

Fig. 4 Reconstructed negative acoustic pressure of (a) linearly folded phase data, (b) real phase data

5. Conclusion

Combining phase contrast method with a non-continuous phase unwrapping algorithm, we successfully measured the optical phase highly modulated at high ultrasound intensity. Further improvement of the proposed method seems to be needed for achieving an SNR high enough for the purpose of ultrasound pressure field quantitative measurement at high intensity.

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References

1. T. A. Pitts, A. Sagers, and J. F. Greenleaf: IEEE Trans. Ultrason., Ferroelect., Freq. Contr. **48** (2001) 1686.
2. S. Harigane, R. Miyasaka, S. Yoshizawa and S. Umemura: Jpn. J. Appl. Phys. **52**,(2013) 07HF07.
3. M. A. Herraez, D. R. Burton, M. J. Lalor, M. A. Gdeisat: Appl. Optics **41**, No. 35, (2002) 7437.
4. D. C. Ghiglia and M. D. Pritt: *Two-Dimensional Phase Unwrapping: Theory, Algorithms, and Software* (Wiley, NY, 1998) p.122.
5. M. J. Crocker: Encycl. Accoust. **1** (1997) 1