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Quantitative Measurement of Ultrasonic Pressure Field using combination of Optical Method and Nonlinear Acoustic Holography

光学的測定と非線形音響ホログラフィー的解析による超音波音場の定量測定

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1. Introduction

In recent years, ultrasound has been widely used for therapeutic purposes such as HIFU (High-Intensity Focused Ultrasound) therapy. To assure safety and efficacy of such application, fast and accurate meaurement of the ultrasonic pressure field is important.

The most common method to measure ultrasound pressure field is hydrophone scanning. However, this method requires very long scanning time and has the risk of disturbing pressure field because of mechanical scanning. We proposed a fast measurement method using optical phase contrast[1-3], in which the optical phase shift caused by the ultrasonic pressure was measured and the 3D pressure field was reconstracted using CT algorithm. This method can quantify a low pressure field very well, but it has a difficulty at high acoustic pressure such as in a HIFU focal region because the optical phase shift wraps[2] at higher pressure.

In this study, we propose a method combining the optical measurement at lower acoustic pressure and nonlinear acoustic holography[3][4] using the measured pressure as the input.

2. Methods

2.1 Optical Phase Contrast Method

Fig.1 shows optical phase contrast measurement setup. Ultrasound pressure field in water creates a modulation of the refractive index, in which further modulates the phase of the field passing through the field. The relationship between optical phase and acoustic pressure can be written as[5]

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

where k_c is the optical wave number, and $\partial n/\partial p$ is the piezo-optic coefficient calculated as 1.32×10^{-10} Pa^{-1} from the water density of 10^3 kg/m^3, and the sound speed of 1500m/s.

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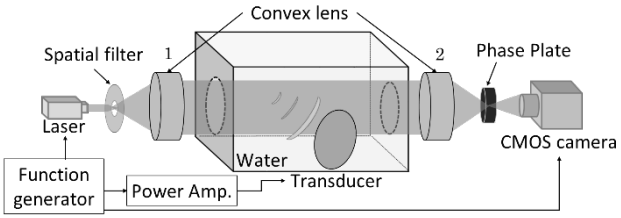

Fig 1　Optical phase contrast measurement setup

In Fig 1, at the focal plane of the second convex lens, the spatial Fourier spectrum of the ultrasound pressure field is formed in such a way that the DC component of the light is focused exactly at the focal point of the lens while the diffracted light component affected by the ultrasound is slightly away from the focal point.

In optical phase contrast method, we introduced two phase plates advancing the phase of DC component by π / 2 and 3π / 2, respectively. The diffracted component was interfered with the phase advanced DC component, whereby its phase modulation was converted intensity modulation written as

$$I_{on+} = |Aexp(j\phi) - \alpha + \alpha exp\{j(\pi/2\}|^2 = A^2 + 2\alpha^2 - 2A\alpha(cos\phi - sin\phi) \qquad (2)$$

$$I_{on-} = A^2 + 2\alpha^2 - 2A\alpha(cos\phi + sin\phi) \qquad (3)$$

Here, A is the optical amplitude, ϕ is the optical phase modulation by the ultrasound field, and α^2 is the intensity of the DC component. The intensity without ultrasonic irradiation can be written as

$$I_{off+} = I_{off-} = A^2 \qquad (4)$$

Using Eq. (2)-(4), the optical phase can be calculated as

$$sin\phi = \frac{(I_{on+} - I_{off+}) - (I_{on-} - I_{off-})}{4A'\alpha} \qquad (5)$$

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

We can reconstruct three dimensional pressure field from this measured phase by applying a CT algorithm.

2.2 Acoustic Holography

The steps of the acoustic holography are as follows,

1. Measure an upstream field of HIFU where optical phase dose not wrap.
2. Using the upstream pressure field as the input, calculate the pressure at the source by numerically back propagating ultrasound.
3. Using the pressure at the source, the field is calculated by numerical simulation of nonlinear forward propagation.

In this way, a HIFU pressure field can be obtained without directly measuring the high pressure in the focal region.

Assuming that the acoustic pressure at the source is proportional to the drive voltage, a various therapeutic level of HIFU field can be obtained by multiplying the source pressure before the numerical nonlinear propagation.

3. Experiment

The pulsed laser (wavelength: 532 nm, SPOT-10-200-532, ELFORLIGHT) was expanded by a spatial filter, collimated by the first convex lens, and focused by the second convex lens after passing through the ultrasound. The projection image was taken by a CMOS camera (ORCA-Flash2.8, Hamamatsu Photonics K.K.).

In this study, an axisymmetric 8-element annular array transducer (outer diameter: 80 mm, inner diameter: 36 mm, focal length: 80 mm, center frequency: 1.4 MHz) was driven at 50 Vpp. The pressure field 40 mm upstream the focal point was measured by the optical method and used in the acoustic holography. The obtained source pressure was multiplied by 6 and 10 times to numerically calculate the pressure field at drive voltages of 300 and 500 Vpp, respectively. The resulting focal pressure was compared with direct measurement by a fiber optic hydrophone (Onda, HFO-690).

4. Result and Discussion

Fig 2 show an upstream pressure field measured by the optical phase contrast method. Fig 3 (a) shows the source pressure field after back propagation of the measured pressure. Fig 3 (b) shows the fields during the numerical nonlinear propagation. The obtained focal pressure waveform compared with direct hydrophone measurement is shown in Fig 4. Good agreement in absolute pressure is seen at both intensities.

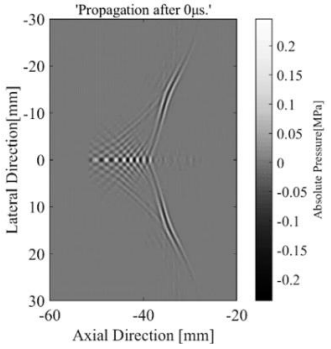

Fig 2 Pressure field measured by optical method

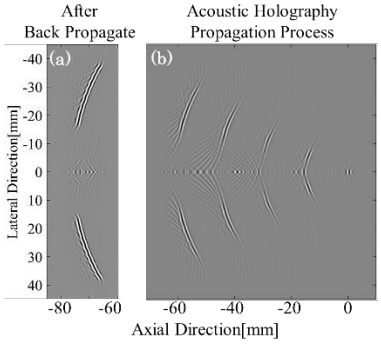

Fig 3 (a) Pressure field after back propagation (b)Process of nonlinear propagation

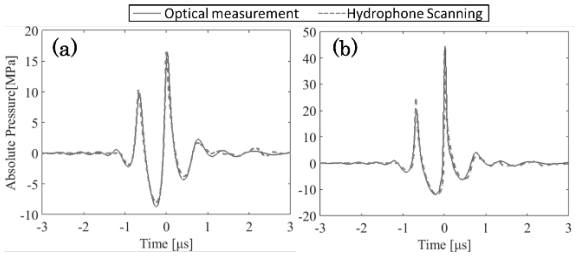

Fig 4 Pressure waveform at focus driven at (a) 300Vpp (b) 500Vpp

5. Conclusion

The combination of optical measurement and acoustic holography provided HIFU fields agreeing with direct hydrophone measurement. Study will be continued further for continuous wave field and non-axisymmetric field.

References

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