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Simulation of Optical Propagation for Phase Retrieval in Shadowgraph of Ultrasonic Field

音場のシャドウグラフにおける位相復元を目的とした光伝搬シミュレーション

Hiroki Hanayama†, Takuya Nakamura, Ryo Takagi, Shin Yoshizawa, and Shin-ichiro Umemura (Tohoku Univ.)

花山 洋貴†，中村 拓也，高木 亮，吉澤 晋，梅村 晋一郎(東北大学)

1. Introduction

Fast and accurate measurement of ultrasound pressure field is demanded from the development of ultrasonic devices. A hydrophone is generally used to measure an ultrasound pressure field, but this measurement needs a long time and may disturb the acoustic field. A shadowgraph method is one of the optical methods enabling fast and noninterfering measurement of ultrasonic pressure field.

In this method, the modulated phase of light caused by the ultrasonic pressure field is measured and a computed tomography (CT) algorithm is apllied to reconstruct the 3D pressure field[1]. However, the pressure field tends to be limited upto several MPa_{pp}, because the approximation of geometrical optics, which has been used to obtain the optical phase from intensity distribution, collapses at a higher accoustic pressure.

In this study, we investigate the usefulness of a method simulating optical propagation without depending on the geometrical optics approximation to overcome the limitation in acoustic pressure.

2. Methods

2.1 Theory of Shadowgraph method

Fig. 1 shows the shadowgraph measurement setup used in this study. The ultrasound propagation in water creates the spatial change in water density and the refractive index which modulates the phase of the incident light. The relation between the modulated optical phase ϕ and the acoustic pressure P can be written as

$$\phi = k_c \frac{\partial n}{\partial P} \int_l \; Pdz \qquad (1)$$

where k_c is the optical wave number, $\partial n/\partial P$ is the piezo-optic coefficient and l is the optical propagation length through the ultrasound pressure field. Plane p0 is set in the pressure field at the imaging plane and plane p1 is an imaging plane set at a certain optical propagation distance from p0. The phase modulation on p0 is converted to the intensity modulation on p1. In this study, the intensity distribution on p0 is almost the same as the intensity distribution on p1 without ultrasonic exposure because the light is collimated.

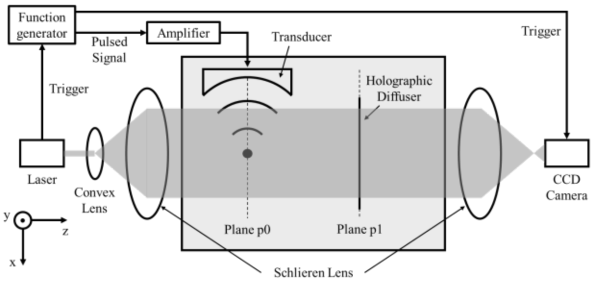

Fig. 1 Optical shadowgraph measurement setup.

2.2 Algorithm of Phase Retrieval[2]

Fig. 2 shows the flow chart of the following algorithm to obtain the phase ϕ in this study. The initial guess for the optical phase distribution on p0 is calculated from the optical intensity distribution on p0 and p1, by geometrical optics approximation[3]. Then, we simulate the optical forward propagation p0 to p1 based on the superimposition principle. Next, using the light combined the simulated phase on p1 and measured intensity on p1, the optical backward propagation from p1 to p0 is simulated. Further next, using the light combined the simulated phase on p0 and measured intensity on p0, the optical forward propagation from p0 to p1 is simulated. This iteration is continued until convergence.

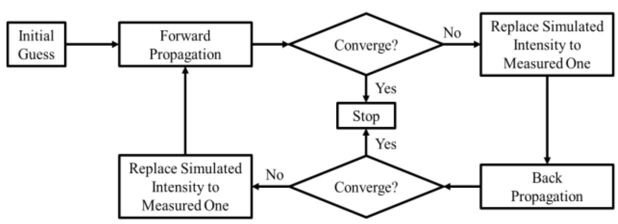

Fig. 2 Flow chart of algorithm for phase retrieval.

hanayama@ecei.tohoku.ac.jp

2.3 Simulation of Optical propagation

In simulation of wave propagation in general, a grid size smaller than the half wavelength is required by principle. In our simulation, however, the grid size was chosen comparable with the spatial resolution of the CCD camera. The computation time was thereby reduced to a realistic range.

3. Experiment

3.1 Confirm Usefulness of Algorithm on Simulation

To confirm usefulness, the above algorithm numerically tested in the simulation assuming an experiment system such as **Fig. 1**.

3.2 Examine Optical Propagation Model

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, a holographic diffuser was placed there, and the axis of an axisymmetric PZT transducer (ϕ: 72 mm, f: 72 mm, center frequency: 1.14 MHz) was placed 40 mm in front of the diffuser. 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 CCD camera was 1 ms. The voltage to drive the transducer was set to 113 V_{pp}. 200 images with and without ultrasonic exposure were captured and averaged for each case.

Optical propagation was simulated using the measured intensity, and the measured and simulated optical intensities were compared.

4. Result and Discussion

Fig. 3 shows a typical result from simulation. The phase modulation was retrieved by the proposed method much better than the conventional geometrical approximation. This result suggests that the proposed method is useful.

Fig. 4 shows the optical intensity on p1 obtained from (a) measurement and (b) simulation. The difference between them is as small as an RMS error of 14.2%, indicating that the employed method to simulate optical propagation was correct. In contrast, the RMS error was 25.0% for the geometrical optics approximation. Further study considering pertinent relaxation of iteration may be needed to practically apply the proposed method to the measurements.

5. Conclusion

The proposed method to numerically simulate optical propagation in shadowgraphy showed its potential usefulness, at least under the condition that the S/N ratio is infinite.

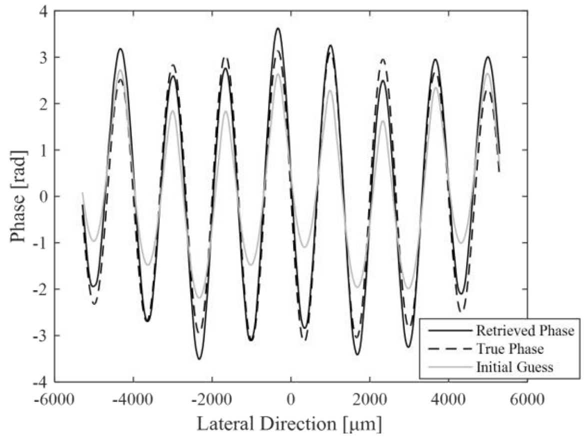

Fig. 3 Modulated phase from simulation

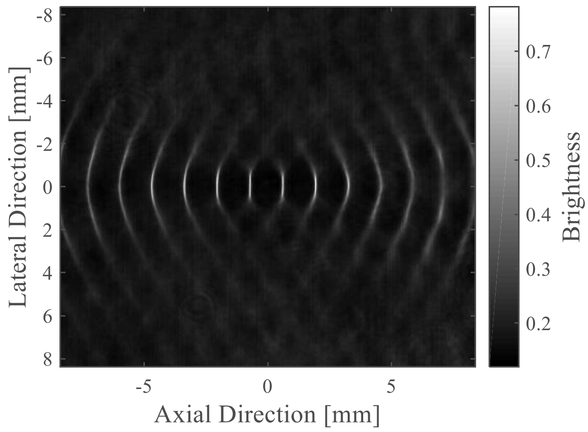

Fig. 4(a) Measured optical intensity on p1.

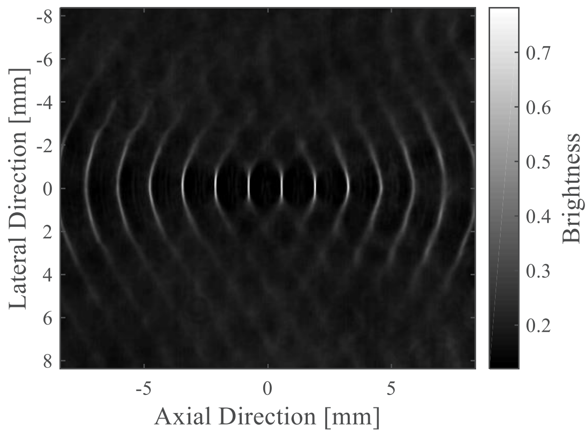

Fig. 4(b) Simulated optical intensity on p1.

References

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