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Measurement of moving objects with phase-shifting digital holography using liquid crystal retarder

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ABSTRACT

We propose a phase-shifting digital holography (DH) method that uses a liquid crystal (LC) retarder for use in the measurement of moving objects. Because LCs are birefringent, they can be used as waveplates for phase-shifting operations. In addition, the phase retardation can be adjusted by varying the LC drive voltage. Mechanical operations are unnecessary in phase shifting when using LCs, but fast interference fringe measurements are possible. The proposed method can be realized by incorporating the LC retarder into a conventional interferometer and is both simple and inexpensive. We performed experiments to verify the effectiveness of the proposed method and confirmed that the method is effective for imaging of the complex amplitude distributions of moving objects.

1. Introduction

In digital holography (DH) [1], phase-shifting methods [2,3] are useful in extraction of the object wave because they can remove any undiffracted waves or twin image waves from the interference fringes. The application of phase-shifting methods to in-line DH makes it possible to measure the fine structures of measurement objects, and these methods have been applied in fields including industrial measurement and bioimaging. Piezoelectric transducers (PZTs) [2,3] and electro-optic (EO) modulators [4] are commonly used as phase-shifting devices. In addition, methods based on variation of the optical path length for the reference wave combined with rotation of the waveplate have been proposed [5]. In the methods that use either a PZT or a waveplate, the required optical system can be constructed simply, but the phase-shifting process requires mechanical operations and it can be difficult to measure the required interference fringes at high speeds. In contrast, while methods that are based on the use of EO modulators have a cost disadvantage, high-speed phase shifting is possible when using these methods. Additionally, methods for the measurement of multiple phase-shifted fringes in a single exposure using either multiple image sensors [6–8], phase-shifting arrays [9], or polarization imaging cameras [10–17] have also been proposed. While these methods can measure the interference fringes at rapid rates, they also have problems in that the optical systems that are required become increasingly complex or the spatial resolution of the image sensor cannot be used fully. When compared with the methods described above, methods that use liquid crystals (LCs) as the phase-shifting devices are capable of rapid phase-shifting and can use the full image sensor resolution. LC retarders [18] and LC spatial light modulators (SLMs) [19–22] have been investigated for use as LC phase-shifting devices. Among these devices, methods based on the use of an LC retarder can be implemented inexpensively and simply.

In a DH method using an LC retarder [18], the phase of the reference wave was shifted by varying the refractive index of the LC. While LCs are birefringent media, phase shifting of LCs is possible without rotation of the polarization plane by aligning the slow axis of the LC with the polarization plane of the incident beam. In a DH method that used an LC-SLM [19], the phase of the incident beam was modulated using a binary grating that was displayed on the LC-SLM. The phase modulation was adjusted by changing the lateral displacement of the binary grating, and the reference wave was obtained by extracting the first-order component of the diffracted wave. When compared with the LC retarder, the PZT that is generally used in phase-shifting methods requires a more complex control system to correct the hysteresis effects caused by closed loop control for high-precision phase-shifting. The control system for the PZT also usually costs several times more than that required for the LC retarder. In addition, phase-shifting with a PZT when using closed loop control means that a settling time of 10 ms or more is required.

In this study, we propose and demonstrate a low-cost, simple, and fast DH optical system that uses a LC retarder to perform fast phase-shifting operations. We intend to establish a method for measurement of the complex amplitude distributions of moving objects using a phase-shifting DH method based on use of the LC retarder while also realizing a fast, simple and inexpensive DH system. LCs are birefringent and

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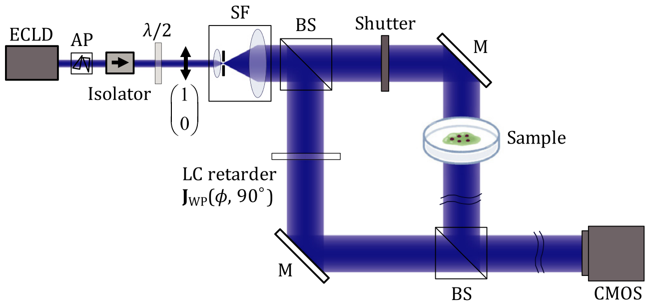

Fig. 1. Optical setup for phase-shifting digital holography using liquid crystal retarder. ECLD: external cavity laser diode; AP: anamorphic prism pair; $\lambda/2$: half-wave plate; SF: spatial filter; BS: beam splitter; M: mirror; CMOS: complementary metal–oxide–semiconductor image sensor.

can be used as waveplates. In addition, the retardation of LCs can be adjusted by varying their drive voltages. The response times of nematic LCs are approximately 10 ms for the rise time and 100 µs for the fall time, and an LC with multiple alignment layers has identical rise and fall times of approximately 100 µs. Therefore, high-speed phase-shifting and interference fringe measurements are also possible when using the LC retarder. While LCs are useful as phase-shifting devices, their fast response times have not necessarily been used in previous studies. We focus on the fast response time of the LC and examine the high-speed phase-shifting DH method experimentally.

2. Principle

The principle of the phase-shifting method using the LC retarder is illustrated below. When the fast axis is the x-axis and the slow axis is the y-axis, the Jones matrix $\mathbf{J}_{\mathrm{wp}}(\phi)$ of a waveplate that produces a retardation ϕ can be expressed as follows [23]:

$$\mathbf{J}_{\mathrm{wp}}(\phi) = \begin{bmatrix} \exp\left(\frac{\mathrm{i}\phi}{2}\right) & 0 \\ 0 & \exp\left(-\frac{\mathrm{i}\phi}{2}\right) \end{bmatrix}. \tag{1}$$

The Jones matrix $\mathbf{J}_{\mathrm{wp}}(\phi, \theta)$ in the case where the fast axis is inclined at an angle θ relative to the x-axis is expressed as $\mathbf{J}_{\mathrm{wp}}(\phi, \theta) = \mathbf{R}(-\theta)\mathbf{J}_{\mathrm{wp}}(\phi)\mathbf{R}(\theta)$, where the two-dimensional rotation matrix is given as $\mathbf{R}(\theta)$; $\mathbf{J}_{\mathrm{wp}}(\phi, \theta)$ is therefore

$$\mathbf{J}_{\mathrm{wp}}(\phi, \theta) = \begin{bmatrix} \cos\frac{\phi}{2} + \mathrm{i}\sin\frac{\phi}{2}\cos 2\theta & \mathrm{i}\sin\frac{\phi}{2}\sin 2\theta \\ \mathrm{i}\sin\frac{\phi}{2}\sin 2\theta & \cos\frac{\phi}{2} - \mathrm{i}\sin\frac{\phi}{2}\cos 2\theta \end{bmatrix}. \tag{2}$$

When light that is polarized at $[1\ 0]^{\mathrm{T}}$ enters an LC retarder with a Jones matrix of $\mathbf{J}_{\mathrm{wp}}(\phi, 90^\circ)$, the phase modulated light represented by $\mathbf{u}(\phi, 90^\circ)$, where

$$\mathbf{u}(\phi, 90^\circ) = \mathbf{J}_{\mathrm{wp}}(\phi, 90^\circ)\begin{bmatrix}1\\0\end{bmatrix} = \begin{bmatrix} \exp\left(-\frac{\mathrm{i}\phi}{2}\right) \\ 0 \end{bmatrix} \tag{3}$$

is obtained. We use $\mathbf{u}(\phi, 90^\circ)$ as a reference wave here. Phase-shifted fringes can then be obtained by adjusting the LC retarder's driving voltage and varying the retardation ϕ. In this study, a two-step method [24,25,8] in which $\phi = 0, \pi$ is used.

Fig. 1 shows the optical system that is used for the proposed method. The system has a simple configuration in which the LC retarder is added to a Mach–Zehnder interferometer. An external cavity laser diode (ECLD; Nichia NUV603E) with a center wavelength of $\lambda = 405$ nm was used as the light source. The anamorphic prism pair (AP) was used to correct the shape of the incident beam from elliptical to circular, and the optical isolator was used to prevent the light from being returned. The half-wave plate (HWP) was used to align the polarization plane of the incident beam with the slow axis of the LC retarder. By aligning the polarization plane of the incident beam to be parallel to the slow axis, it becomes possible to shift the phase without rotating the polarization plane using the LC retarder. The spatial filter (SF) is used to remove noise and distortion from the wavefront. The focal lengths of the two SF lenses are 10 mm and 50 mm, and the beam that passed through the SF was collimated to a diameter of approximately 20 mm. A Thorlabs LCC1411-A LC retarder was used in this case. The image sensor is a Baumer VCXU-50M with a pixel size of 3.45 µm and resolution of 2448 × 2048. The imaging optics are not mounted in the system. The light that is emitted by the ECLD is polarized to $[1\ 0]^{\mathrm{T}}$ using the HWP. After noise removal via use of the SF, the polarized beam is then split using the beam splitter. One of the light beams is modulated by the measurement object to have an amplitude of a_o and phase of ψ, and thus becomes the object wave $\mathbf{u}_o$, which is given by

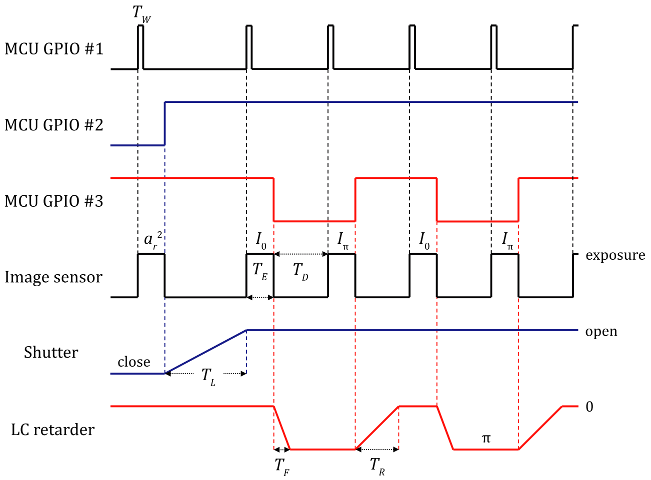

Fig. 2. Timing diagram for the experimental control system. GPIO: general-purpose input/output; T_W: trigger pulse width; T_E: exposure time; T_D: data transfer time; T_L: shutter lag; T_F: LC fall time; T_R: LC rise time.

$$\mathbf{u}_o = a_o \begin{bmatrix} \exp(\mathrm{i}\psi) \\ 0 \end{bmatrix}. \tag{4}$$

The other light beam is modulated to have an amplitude of a_r and phase of $-\phi/2$ by the LC retarder with $\mathbf{J}_{\mathrm{wp}}(\phi, 90^\circ)$, and thus becomes the reference wave $\mathbf{u}_r$, which is given by

$$\mathbf{u}_r = a_r \begin{bmatrix} \exp\left(-\frac{\mathrm{i}\phi}{2}\right) \\ 0 \end{bmatrix}. \tag{5}$$

The resulting interference fringe I_ϕ of $\mathbf{u}_o$ and $\mathbf{u}_r$ is given by

$$\begin{aligned} I_\phi &= |\mathbf{u}_o + \mathbf{u}_r|^2 \\ &= a_o^2 + a_r^2 + 2a_o a_r\left(\cos\psi\cos\frac{\phi}{2} - \sin\psi\sin\frac{\phi}{2}\right). \end{aligned} \tag{6}$$

If $\phi = 0, \pi$, then the interference fringe I_ϕ becomes

$$\begin{aligned} I_0 &= a_o^2 + a_r^2 + 2a_o a_r\cos\psi, \\ I_\pi &= a_o^2 + a_r^2 - 2a_o a_r\sin\psi. \end{aligned} \tag{7}$$

If the intensity of the reference wave a_r^2 is measured beforehand, the amplitude a_o and the phase ψ of the object wave $\mathbf{u}_o$ can then be obtained from I_0, I_π, and $\sin^2\psi + \cos^2\psi = 1$, as shown below [24,25,8]:

$$\begin{aligned} a_o^2 &= \frac{1}{2}\left\{I_0 + I_\pi - \left[4a_r^2\left(I_0 + I_\pi - a_r^2\right) - \left(I_0 - I_\pi\right)^2\right]^{1/2}\right\}, \\ \psi &= \arctan\left(\frac{a_o^2 + a_r^2 - I_\pi}{I_0 - a_o^2 - a_r^2}\right). \end{aligned} \tag{8}$$