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Discussion

Twin-image reduction method for in-line digital holography using periphery and random reference phase-shifting techniques

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ABSTRACT

Digital holography has the twin image problem that unwanted lights (conjugate and direct lights) overlap in the object light in the reconstruction process. As a method for extracting only the object light, phase-shifting digital holography is widely used; however, this method is not applicable for the observation of moving objects, because this method requires the recording of plural holograms. In this study, we propose a twin-image reduction method by combining the "periphery" method with the "random phase-shifting" method. The proposed method succeeded in improving the reconstruction quality, compared to other one-shot recording methods ("parallel phase-shifting digital holography" and "random phase-shifting").

1. Introduction

Digital holography records holograms by using imaging devices such as charge coupled devices (CCDs), and then reconstructs three-dimensional information from the holograms by simulating light propagation on a computer [1]. However, the space bandwidth of CCDs are not wide compared to the photographic plates used in analog holography. Therefore, in-line digital holography whose space bandwidth can be restrained is now widely used despite there being the "twin-image problem" that unwanted lights (conjugate and direct lights) overlap in the object light in the reconstruction process.

Phase-shifting digital holography is used to solve the twin-image problem. However, this method is not applicable for the observation of moving objects, because this method requires plural holograms to be recorded sequentially [2]. In order to solve this problem, "parallel phase-shifting digital holography" which can take phase-shifted holograms in one-shot recoding has been proposed [3,4]. This technique succeeded in the phase imaging of high-speed phenomenon with a high-speed camera. However, this method requires precise alignment between a special polarization device and the imaging device, and interpolation and filtering in the reconstruction process. The image quality is decreased, compared to the original phase-shifting digital holography.

Other methods of solving the twin-image problem are the phase retrieval algorithms that are used in the field of X-ray diffraction microscopes [5–7]. It is difficult to retrieve phase information from only a diffraction intensity pattern, whereas phase retrieval algorithms can retrieve the amplitude and phase information of objects by performing iterative calculations with measured diffraction intensity patterns and known information. Since the proposal of Gerchberg–Saxton (GS) algorithm [5] which was a pioneering retrieval algorithm, a number of other phase retrieval algorithms have been proposed. For example, ptychography [8], which performs phase retrieval with wide-field and high resolution by scanning objects, is being studied. However, ptychography is inadequate for recording the observation of moving objects because it needs to record multiple diffraction intensity patterns sequentially. Recently, the "periphery method" which is a phase retrieval algorithm was proposed [9]. This method is capable of recording moving objects because it requires only one diffraction intensity pattern. However, there is a problem that the periphery method is often trapped in a local solution in the iterative calculation, so that the quality of the retrieved amplitude and phase may be limited.

In this study, we improve the original periphery method using the random phase-shifting [10–12] method and investigate the effectiveness of the proposed method by numerical simulation. We focus on the fact that the reconstruction quality of the periphery method is strongly dependant on the initial value. Therefore, we give an appropriate initial value guessed by the random phase-shifting method to the periphery method. Compared to the

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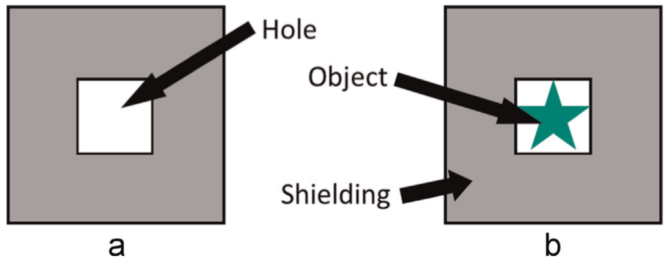

Fig. 1. Diffuser (periphery) and observation object. (a) Diffuser with hole. (b) Observation object placed in the hole.

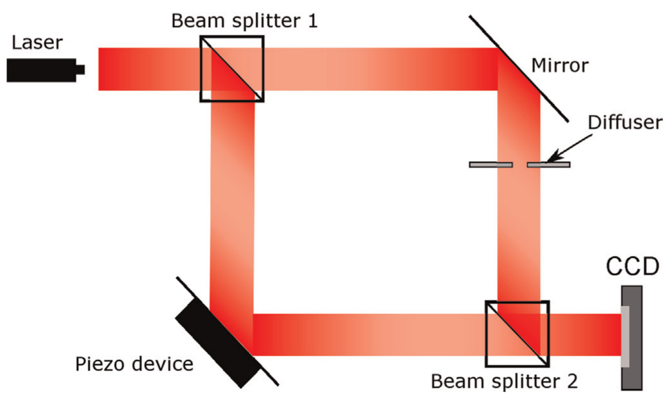

Fig. 2. Recording the complex amplitude of the diffuser using conventional phase-shifting digital holography.

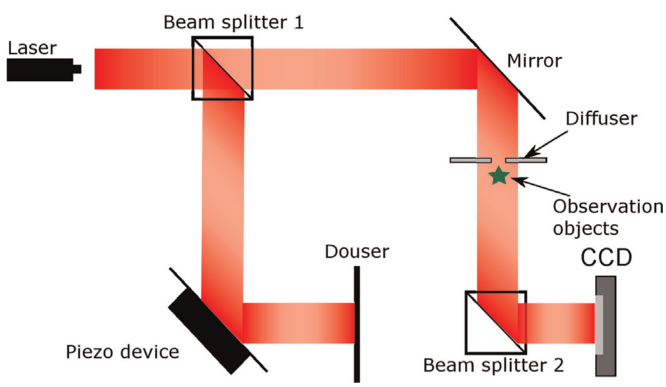

Fig. 3. Recording of hologram. Observation objects are set in the hole of the diffuser.

one-shot recording methods, such as original periphery, parallel phase-shifting and random phase-shifting methods, the proposed method succeeded in improving the reconstruction quality without any changes of the optical setup in the original periphery method.

2. Proposed method

The convergence result and number of iterations for phase retrieval algorithms including the periphery method is affected by the initial value. Conventionally, the reference wave or random phase was used as the initial value; however, such initial value does not include sufficient information for phase retrieval. In this paper, we propose an improved periphery method. The proposed method improves the convergence result by applying the initial

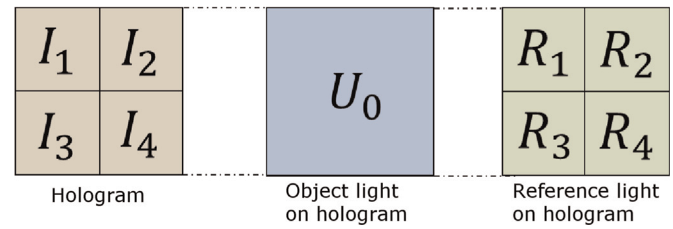

Fig. 4. Relation of the object light and reference light for four adjacent pixels on a hologram plane in the random phase-shifting method.

value near the object light guessed by the random phase shifting method [10].

2.1. Periphery method

The periphery method [9] records a hologram by placing a known complex amplitude, which is referred to as the periphery, around observation objects. As shown in Fig. 1, the original periphery method uses a diffuser as the periphery, which has a hole (Fig. 1(a)) in which observation objects are placed (Fig. 1(b)) . The incident light to the diffuser is widely spread, then the spread light overlaps with the object light. The periphery method is based on an error reduction (ER) method [6], and changes the constraint conditions in the object plane and the detector plane of the ER method to the pre-measured complex amplitude of the diffuser and recoded hologram, respectively. Propagation between the object and detector planes is performed by light propagation calculation. We use the angular spectrum method as the light propagation.

We explain the recording process. Firstly, the complex amplitude of the diffracted light from the diffuser is measured by conventional phase-shifting digital holography [2] as shown in Fig. 2. Secondly, we set observation objects in the hole of the diffuser as shown in Fig. 3. Then a hologram is recorded by interfering the object lights with the diffused light from the diffuser.

Let us reconstruct the object light from the recorded hologram using an iterative calculation. The object light is extracted by the ER method using known information: the recoded hologram and pre-measured complex amplitude of the diffuser. We use the following formula as an initial guess, which is the complex amplitude of the detector plane:

$$U_h(1) = \sqrt{I}\frac{R_h}{|R_h|}, \tag{1}$$

where I is the recorded hologram and R_h is the complex amplitude of the diffuser on the detector plane. Next, we solve the complex amplitude of the object plane $U_{obj}(k)$ by diffraction calculation by the following equation:

$$U_{obj}(k) = F_{ho}\{U_h(k)\}, \tag{2}$$

where $k = 1, 2, 3\ldots$ indicates the number of iterations. The operator $F_{ho}\{\cdot\}$ indicates the diffraction calculation from the detector plane to the object plane. We solve new complex amplitude $U'_{obj}(k)$ by imposing the following constraint condition to $U_{obj}(k)$:

$$U'_{obj}(k) = \begin{cases} U_{obj}(k) & \text{(inside hole)}, \\ R_{obj} & \text{(otherwise)}, \end{cases} \tag{3}$$

where R_{obj} shows the complex amplitude of the diffuser on the object plane which is obtained by inverse diffraction calculation of R_h. We propagate U'_{obj} to the detector plane:

$$U'_h(k) = F_{oh}\{U'_{obj}(k)\}, \tag{4}$$