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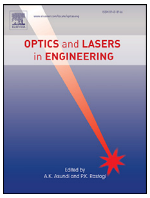

Accuracy concerns in digital speckle photography combined with Fresnel digital holographic interferometry

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ABSTRACT

A combination of digital holographic interferometry (DHI) and digital speckle photography (DSP) allows in-plane and out-of-plane displacement measurement between two states of an object. The former can be determined by correlating the two speckle patterns whereas the latter is given by the phase difference obtained from DHI. We show that the amplitude of numerically reconstructed object wavefront obtained from Fresnel in-line digital holography (DH), in combination with phase shifting techniques, can be used as speckle patterns in DSP. The accuracy of in-plane measurement is improved after correcting the phase errors induced by reference wave during reconstruction process. Furthermore, unlike conventional imaging system, Fresnel DH offers the possibility to resize the pixel size of speckle patterns situated on the reconstruction plane under the same optical configuration simply by zero-padding the hologram. The flexibility of speckle size adjustment in Fresnel DH ensures the accuracy of estimation result using DSP.

1. Introduction

Digital speckle photography (DSP) is a simple and robust method for tracking in-plane deformation. The displacement is determined by numerically cross-correlating the speckle patterns generated on the surface of a scattering object under coherent illumination at the initial and deformed states [1]. A displacement over several tens of speckle diameter can be obtained with subpixel accuracy if crucial parameters such as speckle size and finite window size are properly defined when using DSP [2].

DSP can be combined with interferometry techniques based on speckle effect. Interferometry techniques including electronic speckle pattern interferometry (ESPI) (also named digital speckle pattern interferometry and TV–holography) and speckle shearing interferometry (also known as shearography) allow a measurement of out-of-plane displacement fields in their usual geometric configuration where the object illumination is in the same direction as the field of view of the observation system [3]. Implementing DSP on these interferometry techniques is useful for obtaining simultaneously in-plane and out-of-plane displacements, which have always been of great interest for industrial non-contact metrology applications [4–8]. One necessary condition for obtaining accurate results from DSP is that the speckle size should be larger than two pixels to meet sampling requirement [2]. In all these cases, speckle patterns are imaged onto a CCD camera, which can be sufficiently resolved by correctly setting the imaging aperture.

Digital holographic interferometry (DHI) is another technique which allows measuring out-of-plane movements based on digital holography (DH). Differing from other interferometry techniques, DH records the holograms and reconstructs numerically the object wavefield based on diffraction theory [9,10]. The phase difference of object at two instants relates to the out-of-plane displacements located on each point of the object. On the other hand, the reconstructed amplitude of a diffused object also contains speckles and thus can be used for in-plane displacement measurement. A combination of DHI and DSP provides access to three-dimensional displacement. However, compared with the DSP based on imaged speckle patterns, large bias and standard deviation errors are reported in earlier works when applying DSP on DH reconstructed images [11,12].

In this paper, we present a combination of DSP and phase-stepping Fresnel digital holography, making it possible to measure in-plane and out-of-plane displacement of a large object at long working distance. Our objective is to investigate the causes of low accuracy in in-plane displacement measurement reported in [11,12]. We demonstrate that phase errors caused by slightly divergent reference beam contribute to a complementary speckle displacement. Moreover, the speckle features in the reconstructed plane are not resolved enough to match the speckle

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size requirement for DSP, which leads to systematic errors in in-plane displacement. We show experimentally that the in-plane displacement measurement can be significantly improved after these two sources of error are corrected.

In Section 2 we recall the theoretical basis of DHI and DSP, based on which sources of error existing in in-plane displacement measurement are derived analytically. In Section 3 we describe the setup. In Section 4, we present different experimental results. Each source of error is examined and corrected. Finally some conclusions and discussion are presented in the last section.

2. Theoretical analysis

2.1. Digital holography interferometry combined with digital speckle photography

DH consists of recording the holograms with an array sensor and numerically reconstructing the original wavefield at given distances based on the recorded holograms. During the recording process, reference wave $U_R(\xi, \eta)$ interferes with object wavefield $U_O(\xi, \eta)$ in the plane of CCD detector (ξ, η), forming interference patterns, *i.e.*, holograms $I_H(\xi, \eta)$ given by:

$$I_H = |U_R|^2 + |U_O|^2 + U^*{}_R U_O + U_R U^*{}_O, \tag{1}$$

where the asterisk denotes complex conjugates and the dependency to the coordinates (ξ, η) is omitted for simplicity.

Eq. (1) contains four terms corresponding to three diffraction orders: the 0 order is composed of terms $|U_R|^2 + |U_O|^2$, the $+1$ order $U^*{}_R U_O$ which contains initial information of object wavefield, and –1 order $U_R U^*{}_O$ which is also known as twin image. The $+1$ order is of interest for reconstructing the object wavefield. Under in-line configuration, the unwanted diffraction orders superimposed on the $+1$ order can be eliminated through applying phase-shifting (PS) techniques [13]. This technique requires several captures of holograms whereby corresponding phase shifts are introduced between object and reference arms. For instance, a four-step PS algorithm proposed in [14] aimed at forming a new compound hologram $H_{PS}(\xi, \eta)$ from 4 phase-shifted holograms $I_{H,\,n}(\xi, \eta)$ with n = 0, 1, 2, 3:

$$I_{H,n}(\xi,\eta) = |U_R(\xi,\eta) + U_O(\xi,\eta)\exp(-\mathrm{i}\frac{n\pi}{2})|^2, \tag{2}$$

and

$$\begin{aligned} H_{PS}(\xi,\eta) &= \frac{1}{4}\left[\left(I_{H,0}(\xi,\eta) - I_{H,2}(\xi,\eta)\right) - \mathrm{i}\left(I_{H,1}(\xi,\eta) - I_{H,3}(\xi,\eta)\right)\right] \\ &= U_R^*(\xi,\eta)U_O(\xi,\eta). \end{aligned} \tag{3}$$

If the complex amplitude distribution of the reference wavefront $U_R(\xi, \eta)$ is known, the object wavefield located in the object plane (x, y) at distance z from the hologram plane, $U_O(x, y, z)$, can be retrieved by back propagating the processed hologram $H_{PS}(\xi, \eta)$ according to scalar diffraction theory. Under the paraxial approximation, the reconstructed wavefield at object plane $U_O(x, y, z)$ can be calculated by the Fresnel transform [3,9,10]:

$$\begin{aligned} U_O(x,y,z) = {} & \frac{\mathrm{i}}{\lambda z}\exp\left(-\mathrm{i}\frac{2\pi}{\lambda}z\right)\exp\left[-\mathrm{i}\frac{\pi}{\lambda z}\left(x^2+y^2\right)\right] \\ & \times\iint U_R(\xi,\eta)H_{PS}(\xi,\eta)\exp\left[-\mathrm{i}\frac{\pi}{\lambda z}\left(\xi^2+\eta^2\right)\right] \\ & \times\exp\left[\mathrm{i}\frac{2\pi}{\lambda z}(x\xi+y\eta)\right]d\xi d\eta. \end{aligned} \tag{4}$$

Considering that the hologram is sampled by the array sensor on $M\times N$ pixels with dimensions $\Delta\xi\times\Delta\eta$, it is therefore necessary to digitize Eq. (4), yielding the computation of object wavefield on $M\times N$ discrete points, *i.e.*,

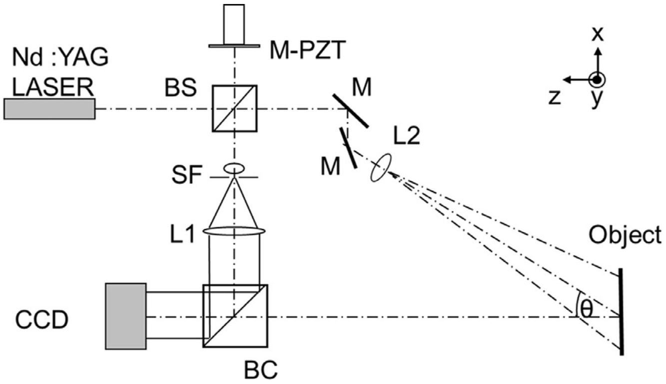

Fig. 1. Schematic of the experimental setup.

$$\begin{aligned} U_O(m,n,z) = {} & \frac{\mathrm{i}}{\lambda z}\exp\left(-\mathrm{i}\frac{2\pi}{\lambda}z\right)\exp\left[-\mathrm{i}\frac{\pi}{\lambda z}\left(\frac{m^2}{M^2\Delta\xi^2}+\frac{n^2}{N^2\Delta\eta^2}\right)\right] \\ & \times\sum_{k=0}^{M-1}\sum_{l=0}^{N-1}U_R(k,l)H_{PS}(k,l) \\ & \times\exp\left[-\mathrm{i}\frac{\pi}{\lambda z}\left(k^2\Delta\xi^2+l^2\Delta\eta^2\right)\right]\exp\left[\mathrm{i}2\pi\left(\frac{km}{M}+\frac{ln}{N}\right)\right]. \end{aligned} \tag{5}$$

Comparing with the definition of Inverse Discrete Fourier Transformation (IDFT), the sum part in Eq. (5) can be rewritten as IDFT of the product $U_R H_{PS}\exp\left[-\mathrm{i}\pi/\lambda z\left(k^2\Delta\xi^2+l^2\Delta\eta^2\right)\right]$, which can be calculated efficiently with fast Fourier transform (FFT) algorithm. The reconstruction of H_{PS} with Eq. (5) gives the both the amplitude A_O and the phase map φ_O of the observed object at distance z, where

$$A_O(m,n) = |U_O(m,n)|, \tag{6}$$

and

$$\varphi_O(m,n) = \arg\left[U_O(m,n)\right]. \tag{7}$$

For two states of the object where a displacement $\vec{d}(d_x, d_y, d_z)$ has taken place, after reconstruction using Eqs. (5)–(7), the difference between the phase at initial state $\varphi_{O,\,ini}$ and the phase at displaced state $\varphi_{O,\,disp}$ is related to optical path difference caused by applied displacement given by

$$\Delta\varphi_O = \varphi_{O,\ disp} - \varphi_{O,\ ini} = \vec{d}\cdot\vec{S}, \tag{8}$$

where $\vec{S}$ stands for the sensitivity vector which is determined by the directions of illumination and observation [3]. In accordance with the geometrical setup depicted in Fig. 1, Eq. (8) can be written with the illuminating angle $\theta(m, n)$ on each point of object:

$$\Delta\varphi_O(m,n) = \frac{2\pi}{\lambda}[\sin\theta(m,n)d_x + (1+\cos\theta(m,n))d_z]. \tag{9}$$

When applying DHI, the amplitude images $A_{O,\,disp}(m, n)$ and $A_{O,\,ini}(m, n)$ which carry the speckle patterns of two states are also obtained during reconstruction. The amplitude images can be processed by DSP for in-plane displacement measurement. DSP technique consists of computing the speckle displacement between two digitized speckle patterns. More precisely, in the algorithm proposed by Shjödahl [1], DSP computes the cross-correlation of subimages (typically 32 × 32 pixels) taken at the same location in two speckle patterns. Locating the correlation peak gives the displacement measurement with subpixel accuracy. Extensive research has been carried out on the accuracy concerns of DSP such as the influence of finite window size, speckle size and measurement range based on imaging systems [1,2,15], which should be re-adapted into DH configurations.

2.2. Influence of phase errors of DH on DSP measurement

The reconstruction of object wavefield can be fully achieved during DH on the premise of reference wave parameters in the detector plane