One-shot in-line digital holography based Hilbert phase-shifting

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Received January 9, 2009

A novel one-shot in-line digital holography based on Hilbert phase-shifting is proposed. By weakening the ratio of object wave to reference wave and applying natural logarithmized operation on the in-line digital hologram, the real part of object wave can be well extracted. Then utilizing Hilbert transform to digitally realize $\pi/2$- phase shift, which would make it possible to reconstruct the object wavefront from a single-exposure in-line digital hologram. Preliminary experimental results are presented to confirm the proposed method. This technique can be used for real time imaging or monitoring moving objects.

OCIS codes: 090. 1995, 050.5080.
doi: 10.3788/COL20090712.0000.

Digital holography is a useful technique for recording the fully complex field of a wavefront, which provides the ability of recording information about the three-dimensional (3D) object at various depths simultaneously. Digital holography has been extensively used in many fields such as encryption[1], shape measurement[2,3], 3D recognition[4], and microscopy[5,6]. Among different digital holography techniques, in-line geometry may exhibit better performance than off-axis geometry in the effective utilization of the number of pixels and the pixel size of an imaging device. However, the main drawback of in-line digital holography is the inability to separate the conjugate image from the desired reconstructed image by using single-exposure hologram. Usually a phase-shift technique is applied to eliminate the conjugate image in a in-line digital hologram[7,8]. However it requires three or four exposure holograms for a fully complex field to be obtained, which makes it impossible for real time recording of the dynamic image. When the object wave is weakened compared with the reference wave, a new reconstruction method for in-line digital holography based on two intensity images was proposed[9]. By using two charge coupled device (CCD) or complementary metal oxide semiconductor (CMOS) sensors, it can be used for real time digital holography imaging. In the field of phase-shift digital holography, a method named two-shot holography was proposed[10], which needs two phase-shifted holograms. Nevertheless it is only suitable for uniform intensity distribution object. Recently parallel quasi-phase-shifting digital holography was also proposed[11]. The technique can implement four kinds of phase-shifting at a time and realize one-shot in-line digital holography by using a pixilated phase-shifting array device in reference beam. However the phase-shifting array device is wave dependent and difficult to be produced. Another method is to record two phase-shifting holograms simultaneously with orthogonal polarizations[12]. However it needs recording the intensity distribution of object wave beforehand and utilizing special polarization CCD camera to obtain two phase-shift digital holograms from a one-shot digital hologram.

It is well known that Hilbert transform can introduce a signal with $\pi/2$-phase shift and has been widely used in one-dimensional time signal processing such as time delay estimation and phase demodulation. Recently Hilbert transform has been reported to be utilized in interference phase demodulation from a single inference signal[13]. The 3D image reconstruction has been performed from the acquired interference image with a discrete Hilbert transform[14]. The Hilbert transform is also applied for phase analysis of a Dynamic electric speckle interference signal[15]. The data processing is performed in temporal domain. And the phase change at any single pixel is obtained.

In this letter, we propose a novel method for in-line digital holography by using the Hilbert digital phase-shifting in space domain. This method only needs a one-shot digital hologram. It also does not require special CCD sensor for digital hologram recording. The phase-shift digital hologram is obtained by digital image processing. Since only a one-shot hologram is required, the proposed method is insensitive to the external environment noise such as vibration and fluctuation, and it is suitable for real time imaging.

A typical transmission configuration for recording in-line digital hologram is shown in Fig. 1. The laser, as a coherent source, is expanded and collimated to a plane wave which is split into two parts by a beam splitter (BS1). One is used as the object wave, which passes the

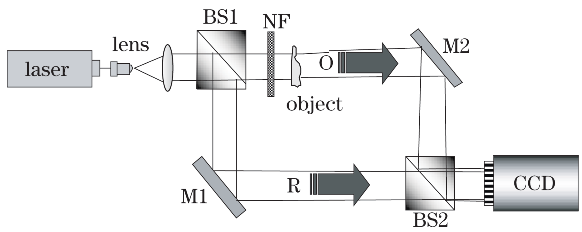

Fig. 1. Recording configuration of in-line digital holography. O: object wave; R: reference wave.

neutral-density filter NF and illuminates the object. The other is used as the reference wave. The mirror M1 that reflects the reference wave is oriented such that the reference wave illuminates the CCD nearly parallel with the object wave. Then the two waves are combined by another beam splitter (BS2). The interference pattern (digital hologram) is recorded by a CCD sensor.

For simplicity, we adopt one-dimensional function for analysis. The digital hologram recorded by the CCD can be written as

$$I(x) = [R\mathrm{e}^{\mathrm{j}2\pi fx} + O(x)][R\mathrm{e}^{\mathrm{j}2\pi fx} + O(x)]^*, \tag{1}$$

where * denotes complex conjugation, R is a real constant that denotes the amplitude of the reference wave, f is the spatial frequency that approximates to zero and denotes the incident direction of the reference wave, $O(x)$ is the object wave. Then divid Eq. (1) by R^2 which is obtained by recording reference wave intensity beforehand, we can get

$$\frac{I(x)}{R^2} = \left[1 + \frac{O(x)\mathrm{e}^{-\mathrm{j}2\pi fx}}{R}\right]\left[1 + \frac{O(x)\mathrm{e}^{-\mathrm{j}2\pi fx}}{R}\right]^*. \tag{2}$$

By adjusting the neutral-density filter (NF) in object wave path, the object wave is weakened compared with the reference wave, and then Eq. (2) can be approximated as

$$\frac{I(x)}{R^2} = \exp\left[\frac{O(x)\mathrm{e}^{-\mathrm{j}2\pi fx} + O^*(x)\mathrm{e}^{\mathrm{j}2\pi fx}}{R}\right]. \tag{3}$$

The error of this approximation is $\left|O^2(x)\right|/2R^2$, i.e., if the ratio between the amplitude of the object and the reference wave is weaker than 0.1, the error caused by the approximation is less than 0.5%[9]. Then applying natural logarithmized operation on Eq. (3), we can get the real part of the object wave

$$\log\frac{I(x)}{R^2} = CRe\left\{O(x)\mathrm{e}^{-\mathrm{j}2\pi fx}\right\}, \tag{4}$$

where $C = 2/R$ is a real constant which will not impact the object wave front.

It is well known that Hilbert transform can introduce a real signal $\pi/2$-phase shift and consequently make the imaginary part of complex signal corresponding to the real signal. The Hilbert transform is defined by[16]

$$h(x) = -\frac{1}{\pi t} * f(x), \tag{5}$$

where * denotes the convolution. Then the complex amplitude of the object wave is obtained by

$$O(x)\mathrm{e}^{-\mathrm{j}2\pi fx} = \log\frac{I(x)}{R^2} - \mathrm{j}\frac{1}{\pi t} * \log\frac{I(x)}{R^2}. \tag{6}$$

Finally we can reconstruct the object image by using Fresnel diffraction formula. From Eq. (6) we can see that the obtained complex amplitude of the object wave is modulated by the reference plane wave, i.e., $\mathrm{e}^{-\mathrm{j}2\pi fx}$, which will make the reconstructed image f coordinate shift. Otherwise we can also remove the phase aberration by the fitting procedures[17].

Here an experiment is given to demonstrate this technique. As shown in Fig. 1, the He-Ne laser with wavelength of 633 nm is used as a coherent light source. A CCD with size of 3.6×2.7 (mm) and pixels of 640×480 is used as the sensor. The imaging object is a grating with spatial frequency of 10 mm^{-1}, as shown in Fig. 2(a). The stripe structures appearing in Fig. 2(a) may result from moiré effect. The distance from grating to CCD is 275 mm. The ratio between the intensity of the object and reference wave is set to about 0.1. The recording one-shot in-line hologram is shown in Fig. 2(b). After divided by the reference wave intensity and the logarithmized operation, the real part of object wave is extracted, as shown in Fig. 2(c). Then performing one-dimensional Hilbert transform along portrait of Fig. 2(c), the quadrature phase-shifting image is obtained, as shown in Fig. 2(d). Compared Figs. 2(c) with (d) we can clearly find the stripes shifting along portrait after Hilbert transformation. In this way the complex amplitude of the object wave is obtained by combining Figs. 2(c) and (d).

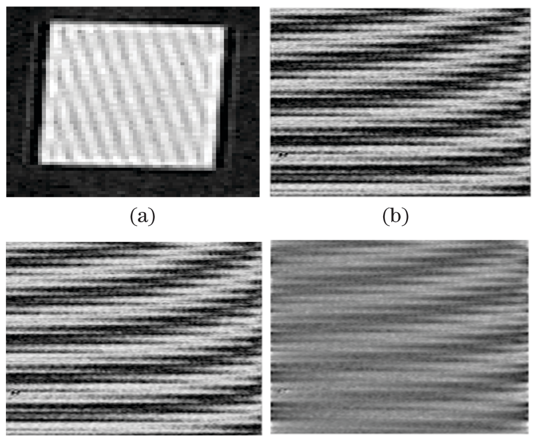

Fig. 2. (a) Imaging object; (b) in-line digital hologram; (c) real part of object wave; (d) quadrature phase-shifting image.

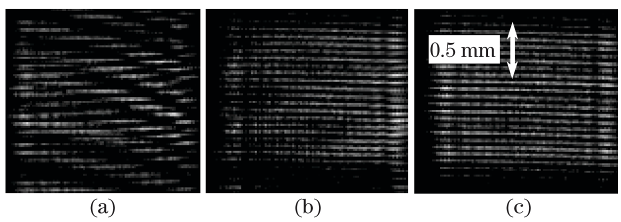

Fig. 3. Reconstructed images from (a) in-line digital hologram as Fig. 2(c); (b) Hilbert-shifting digital holograms as Figs. 2(c) and (d); (c) three-step phase-shifting in-line holograms.

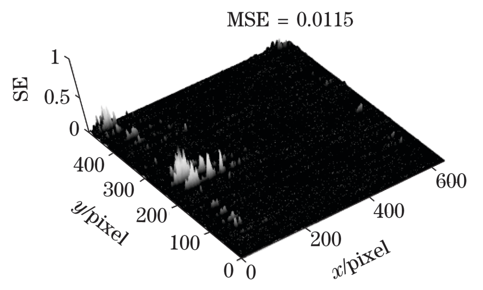

Fig. 4. SE distribution image of Figs. 3(b) and (c).

Then we try to reconstruct the object image by using Fresnel diffraction algorithm. Figure 3(a) shows the image reconstructed from the in-line digital hologram as Fig. 2(b). The strong direct component has been filtered out by high-pass filtering. It can be seen that the reconstructed image is interfered by the conjugate image with severity. The details of image are blurry. Figure 3(b) is the reconstructed image from Hilbert phase-shifting digital holograms, i.e., Figs. 2(c) and (d). For comparison, we also provide an object image shown in Fig. 3(c), which is reconstructed from three-step phase-shifting in-line digital holograms. Comparing Figs. 3(b) with (c) it can be seen that the reconstructed image with our proposed Hilbert phase-shifting method has almost the same quality with one of three-step phase-shifting in-line digital holography. The details of grating can be distinguished very well. Figure 4 shows the square error (SE) distribution image of Figs. 3(b) and (c). And the mean square error (MSE) of Figs. 3(b) and (c) is 0.0115, which can be used as a image quality metric of the reconstructed image by the proposed method in comparison with the reconstructed image by the conventional three-step phase-shifting method. The MSE is defined as

$$\mathrm{MSE} = \frac{\sum_{n=1}^{N}\sum_{m=1}^{M} SE(m,n)}{M \times N}, \tag{7}$$

where $\mathrm{SE}(m,n) = (I_O(m,n) - I'_O(m,n))^2$ is the SE of Figs. 3(b) and (c), I_O denotes the grayscale of Fig. 3(b), I'_O denotes the grayscale of Fig. 3(c), and M and N denote the total pixels of the image.

In summary we propose a novel one-shot in-line digital holography based on the Hilbert phase-shifting. The digital hologram is recorded on condition that the object wave is adjusted weaker than the reference wave. The quadrature phase-shifting hologram is obtained by the Hilbert transforming of logarithmized digital hologram. This technique only needs a single-exposure in-line digital hologram. The special CCD or CMOS sensor is not required for hologram recording. The good quality of the proposed technique has been demonstrated by the experiment. We believe that this technique can be used for real-time imaging and monitoring. However, a complementary explanation is needed. It is that a two-dimensional Hilbert transform[18] is required when the object wave is two dimensional, because the interference fringes will run along two directions.

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