Simple and robust digital holography for high-resolution imaging

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Based on the point spread function of holographic system, the lateral resolution of digital holographic imaging system without any pre-magnification is studied. The expression of resolution limitation of holographic imaging system is thus presented. We investigate the possibilities to improve the lateral resolution. The simple experimental setup with an off-axis arrangement is built. By using a U.S. Air Force (USAF) test target as microscopic object, the recorded holograms are reconstructed digitally based on the principle of Fresnel diffraction. The lateral resolution of 2.76 μm without any pre-magnification is demonstrated experimentally, which matches the theoretical prediction well.

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Digital holography, a new imaging technique that implements digitally the principle of holography, is particularly well suited for characterization of microstructure such as surface shape, surface nanostructures and surface roughness. As an advanced optical diagnostic tool, digital holography allows to provide the phase information and the intensity information simultaneously within a sub-second interval[1−4]. Therefore, digital holography has been paid wide attention to in recent years[3−8].

High resolution is the permanent pursuit in microscopic imaging. Many methods used to improve the imaging resolution have been proposed[9,10]. However, there exists some difference about the concept and the expression of the imaging resolution in literatures[1,11,12]. Therefore, it is very important to study the imaging resolution of the holographic system.

Holographic recording with high quality is the committed step in digital holography. Usually, Nyquist sampling theorem and the separation condition of the three parts of reconstructed optical field (the 0, +1, and −1 order images) must be met simultaneously in recording process. In digital holographic microscopy, one of the commonly used configuration is lensless Fourier transform setup, which has many advantages compared with other configurations, such as the accurate intensity image and the very small allowable recording distance for micro-objects[13]. Evidently, the high-resolution image can be obtained by decreasing the imaging area of the investigated object and recording distance, but this decrease is very limited. We found that the lateral resolution can be improved effectively by deviating the separation condition properly.

The schematic plan for recording the lensless off-axis Fourier transform hologram is shown in Fig. 1, where x_0-y_0 denotes the Cartesian coordinates in the object plane, and x-y denotes the coordinates in the hologram plane, z-axis passes through the center of the two planes perpendicularly. The reference point source $\delta\left(x_0 - x_\mathrm{r}, y_0 - y_\mathrm{r}\right)$ is in the object plane. The hologram recording distance is z_0.

According to Refs. [13,14], under the condition of Fresnel approximation, the one-dimensional (1D) point-spread function (PSF) of the digital holographic imaging system is written as

$$\mathrm{PSF} = C\mathrm{sinc}\left(N\Delta x \frac{x_i - x_0}{\lambda z_0}\right) * \left\{\exp\left[-\frac{j\pi}{\lambda z_0}\left(x_i - x_0\right)^2\right]\mathrm{rect}\left(\frac{x_i}{\alpha\Delta x}\right)\right\}, \quad (1)$$

where C is a complex constant, $*$ denotes the convolution operator, and α denotes the fill factor of the charge-coupled device (CCD) camera. From Eq. (1), we can see that the limit distance of the two closest point resolved by the digital holographic system in the object plane is

$$\Delta x_i = \frac{\lambda z_0}{N\Delta x}. \quad (2)$$

It expresses the lateral resolution limitation of the digital holographic imaging system without any pre-magnification. On the other hand, for the digital hologram with large numerical aperture (NA), the lateral resolution limitation becomes[13]

$$\Delta x_i = \frac{0.5\lambda}{\mathrm{NA}} = 0.5\lambda\sqrt{\left(\frac{2z_0}{N\Delta x}\right)^2 + 1}, \quad (3)$$

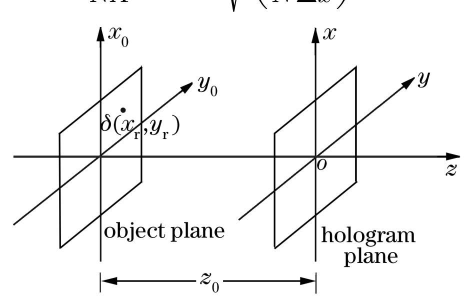

Fig. 1. Scheme for recording off-axis lensless Fourier transform holograms.

where NA denotes the recording numerical aperture of the CCD. Then Eq. (2) can be thought of as the case of Eq. (3) under paraxial approximation.

From Eqs. (2) and (3), we can see that for the given CCD, the smaller the recording distance is, the more high-frequency information can be received by the CCD. This means the possibility of the higher imaging resolution. However, in order to meet the Nyquist sampling theorem, the relationship between the recording distance z_0 and the position of the reference point source should satisfy[13]

$$x_{\mathrm{r}} \leq \frac{\lambda z_0}{2\Delta x} - \frac{X}{2}, \quad y_{\mathrm{r}} \leq \frac{\lambda z_0}{2\Delta y} - \frac{Y}{2}, \tag{4}$$

where X and Y are the sizes of the illuminated area of the object in the two orthogonal directions, Δx and Δy are the pixel pitches of the CCD camera array in the two directions, and λ is the wavelength of laser source. Also, to separate the spectrum of the hologram, the off-set of the reference point source has to meet

$$x_{\mathrm{r}} \geq \frac{3X}{2}, \quad y_{\mathrm{r}} \geq \frac{3Y}{2}. \tag{5}$$

In Eqs. (4) and (5), the equalities mean the critical separation and the critical sampling. In this special case, the allowable limitation recording distance is equal to the minimum value, which depends on the off-set and corresponds to the available imaging resolution. With the smaller off-set, we have the shorter limitation recording distance and achieve the higher available imaging resolution.

Usually in the holographic recording process, the illuminated area of the object cannot be further decreased and is larger than the imaged area which we are interested in. Thus, with the smaller imaged area that is kept not being overlapped during the reconstruction, it is possible to use the smaller off-set to correspondingly achieve higher imaging resolution. Supposing that the dimension of the imaged area at x direction is X_{r}, the new allowable minimum off-set, obtained by considering the previous separation condition, is

$$x_{\mathrm{r\,min}} = \frac{3X_{\mathrm{r}}}{2}. \tag{6}$$

The corresponding minimum recording distance, which is calculated by Eq. (4), becomes

$$z_{0\,\mathrm{min}} = \frac{3X_{\mathrm{r}} + X}{\lambda}\Delta x. \tag{7}$$

It is evident that the optimal off-set of the reference source is proportional to the size of the imaged area. As long as the size of the imaged area is specified, the best imaging resolution for that area and the corresponding optimal off-set can be given from Eqs. (3), (6), and (7).

In order to verify the validities of the above analysis, we have conducted the experiments. The optical setup for recording lensless Fourier transform digital holograms, which is a Mach-Zender interferometer designed for transmission imaging of micro-objects, is shown in Fig. 2. The light with a wavelength of 532 nm from the frequency-doubled solid state Nd:YAG laser is

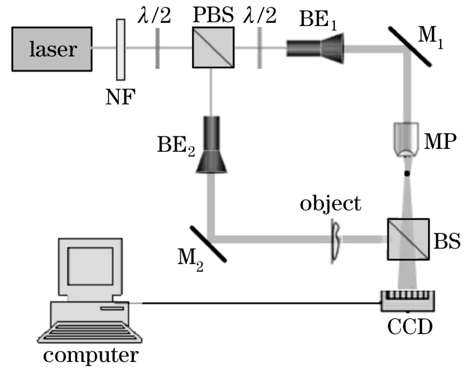

Fig. 2. Optical setup for recording digital off-axis lensless Fourier transform holograms. NF: neutral filter glass; $\lambda/2$: half-wave plate; BE: beam expander; M: mirror; BS: beam splitter.

split into two beams through a polarization beam splitter (PBS). Each beam is expanded and collimated. One beam is focused with a microscope objective (MP) on to a focal point P. A pinhole is placed at the point P to produce a spherical reference wave. Another beam is used to illuminate the object. The digital holograms are recorded by a SensiCam CCD sensor, which has an array of 1317×1035 pixels with 6.8×6.8 (μm) pixel size. The recording distance from the object plane to the CCD sensitive chip is about 51 mm, which is very close to the theoretical value calculated by Eqs. (5) and (7). Thus, the resolution limit is expected to be approached with this setup.

A digital hologram recorded experimentally is presented in Fig. 3(a), which is padded with zeros to form the array of 1318×1318 pixels to avoid the distortion of the reconstructed image. The central part of the hologram is magnified to illustrate the details, as shown in Fig. 3(b). From Figs. 3(a) and (b), we can see that the hologram quality is rather good. There is less noise from the scattered light and the contrast is reasonable.

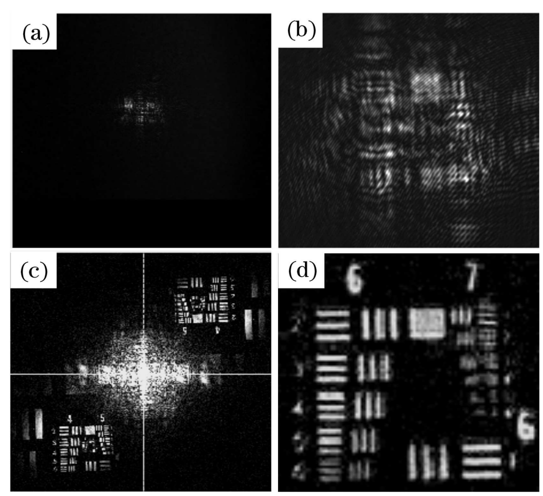

Fig. 3. Digital hologram recorded with the setup shown in Fig. 2 and its intensity image reconstructed with Fresnel method. (a) Recorded hologram; (b) magnified image of the central part in (a); (c) intensity image; (d) magnified image of the left-down part of (c).

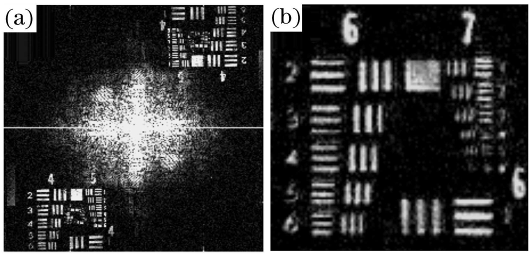

Fig. 4. Reconstructed image at the recording distance of 40 mm. (a) Reconstructed image; (b) magnified image of the left-down part in (a).

The holographic image of the object is then numerically calculated from the resized hologram by using Fresnel diffraction integral, as shown in Fig. 3(c). Figure 3(d) is the magnification of the left-down part in Fig. 3(c). The finest target part resolved corresponds the first element of the seventh group with a line width of 3.91 μm along both horizontal and vertical directions. According to Eq. (3), the theoretical limit resolutions along the orthogonal directions are 3.04 and 3.86 μm, respectively.

After decreasing the off-set of the reference point source a little, the digital hologram is recorded at the distance of 40 mm from the object. The corresponding intensity image reconstructed with Fresnel transform method is shown in Fig. 4. As shown in Fig. 4(a), the reconstructed first-order image is partially overlapped with the zeroth-order diffraction term. Figure 4(b) is the magnification of the left-down part in Fig. 4(a). It is evident that the fourth element of the seventh group with a line width of 2.76 μm can be resolved clearly at the horizontal direction. Vertically, the finest target part resolved corresponds the third element of the seventh group with a line width of 3.10 μm. The lower resolution along vertical direction make the horizontal lines of the seventh group a little shorter. According to Eq. (3), the theoretical resolutions along the orthogonal directions are 2.39 and 3.04 μm, respectively. Therefore, the experimental results match the theoretical prediction very well. It is proved that approaching the resolution limit is possible in digital holography.

If a higher resolution limit is pursued, a microscope objective is usually included into the holographic system. It produces a magnified image of the object that is used for the hologram recording.

In conclusion, we have obtained the lateral resolution limit based on the PSF of the digital holographic imaging system. Besides, we have built a simple experimental setup to record the off-axis lensless Fourier hologram. By decreasing the off-set of the reference point source and the recording distance properly, as well as by holding the Nyquist sampling condition, the lateral resolution of the numerically reconstructed image can be improved effectively. Further improvement in lateral resolution can be achieved by use of a pre-magnification digital holographic system. The validities of the theoretical analysis are demonstrated experimentally.

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