Numerical correction of splicing dislocation between sub-holograms in synthetic aperture digital holography using convolution approach

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We propose a new correction method for the splicing dislocation of sub-holograms in synthetic aperture digital holography. By adjusting the splicing distances between sub-holograms during the numerical reconstruction process using the convolution approach, the influence of non-paraxial aberration for the quality of the synthetic reconstructed image is avoided and synthetic reconstructed images corresponding to different splicing distances are obtained. Then, the accurate splicing distance between sub-holograms is determined by evaluating the quality of the corresponding synthetic reconstructed images. Accurate correction for the splicing dislocation of sub-holograms is achieved and high-quality reconstructed images without non-paraxial aberration are obtained.

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In synthetic aperture digital holography (SADH)[1−11], a series of sub-holograms is recorded with displacement of the CCD target on the hologram recording plane, after which the synthetic aperture digital hologram is obtained according to the default splicing distances between the sub-holograms. By using the synthetic aperture digital holographic system, a holographic image with larger area and higher resolution can be obtained. Such images have potential applications in digital holographic microscopy[6], biological tissue observation[10,12], deformation measurement[11], and so on. However, because of the displacement tolerance of the apparatus used for controlling the movement of charge-coupled device (CCD), the actual splicing distances between sub-holograms are usually deviated from the default ones. The splicing dislocation between sub-holograms will render the synthetic reconstruction image illegible and badly affect the quality of the reconstruction result. According to the cross-correlation function of the overlapping portions of the adjacent sub-holograms, the relative displacement of sub-holograms can be determined, after which the accurate synthetic aperture digital hologram can be obtained by image mosaic for reconstruction[2]. However, this method cannot be implemented if overlapping portions do not exist between the adjacent sub-holograms. To overcome this problem, we propose another method for correcting the splicing dislocation between sub-holograms in which the corresponding synthetic holographic images of the adjacent sub-holograms are reconstructed with arbitrary splicing distances, after which we determine the accurate splicing distance by assessing the quality of the synthetic reconstruction images corresponding to different splicing distances between sub-holograms[9]. The application of this method is not restricted by the overlapping circumstances of sub-holograms. Nevertheless, in this correction method, the adjustment of the splicing distances between the sub-holograms is achieved with the Fresnel transform method[13] (called "Fresnel approximation approach"), which introduces non-paraxial aberration into the reconstructed image when the paraxial approximation[14] is not satisfied during the recording procedure of synthetic aperture digital hologram. The quality of the synthetic reconstruction image will be affected by the non-paraxial aberration, as well as by the splicing dislocation of the sub-holograms, resulting in the inaccurate judgment of the actual splicing distances between sub-holograms by assessing the quality of the corresponding synthetic reconstruction images. To solve this problem, in this letter, we propose a new approach for correcting the splicing dislocation between sub-holograms, in which the adjustment of the splicing distances between sub-holograms is achieved with the convolution approach[15]. This new correction method can avoid the non-paraxial aberration that affects the quality of the synthetic reconstruction image. Therefore, the quality of the synthetic reconstruction image is only affected by the splicing dislocation of sub-holograms. The accurate splicing distance between adjacent sub-holograms can be determined by assessing the quality of the corresponding synthetic reconstruction images when the paraxial approximation is not satisfied during the recording procedure of synthetic aperture digital hologram.

As two mainly used numerical reconstruction methods in digital holography, the Fresnel transform and the convolution approaches are deduced from the numerical simulation of the Fresnel diffraction formula and the Fresnel–Kirchhoff diffraction formula, respectively. The former formula is the simplification of the latter one under the paraxial approximation condition. Therefore, if the paraxial approximation is not satisfied during the hologram recording process, the digital hologram should be reconstructed using the convolution approach, rather than the Fresnel transform method. Otherwise, the object wavefronts cannot be reconstructed

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with sufficient accuracy, thereby affecting the quality of the reconstructed image[16,17]. The resulting degradation of the image quality is called non-paraxial aberration of the holographic reconstructed image. By reconstructing holographic images from the sub-holograms with different splicing distances using the convolution approach, the influence of non-paraxial aberration for the quality of the synthetic reconstruction image can be avoided when the paraxial approximation is not satisfied during the recording procedure of synthetic aperture digital hologram. Therefore, the quality of the synthetic reconstruction image is only affected by the splicing dislocation of the sub-holograms. The accurate splicing distance between sub-holograms can then be determined by assessing the quality of the corresponding synthetic reconstruction images.

The reconstruction coordinates of the synthetic aperture digital hologram is shown in Fig. 1, where O and P are the centers of the synthetic aperture digital hologram (I) and the sub-hologram (I_n), respectively, and the distances between them in the x and y directions are a and b, respectively. To make the view field of the synthetic reconstruction image sufficiently large, the sub-hologram is firstly transformed into an $M_H \times N_V$ array by padding the original hologram with zeros. Assuming that the spectrum of the sub-hologram (I_n) is $U_{In}(f_x, f_y)$ and the spectrum component of the synthetic aperture digital hologram corresponding to the sub-hologram (I_n) is $U'_{I_n}(f_x, f_y)$ respectively, the following relationship can be established based on the phase shift principle of Fourier transform:

$$U_{I'_n}(f_x, f_y) = U_{I_n}(f_x, f_y) \exp\left[-\mathrm{j}2\pi(f_x a + f_y b)\right], \quad (1)$$

where $f_x = m/(M\Delta x_H)$, $f_y = n/(N\Delta y_H)(-M/2 \leqslant m \leqslant M/2-1, -N/2 \leqslant n \leqslant N/2-1)$ are the spatial frequencies in the x and y directions, respectively, and Δx_H, Δy_H are the pixel size of CCD in the corresponding directions, respectively. With the convolution approach, the component of the synthetic reconstruction image corresponding to the sub-hologram (I_n) can be obtained by

$$u_{I_n}(x', y') = \mathcal{F}^{-1}\Big\{U_{I'_n}(f_x, f_y) \cdot \exp\left[\mathrm{j}\frac{2\pi d}{\lambda}\sqrt{1-(\lambda f_x)^2-(\lambda f_y)^2}\right]\Big\}, \quad (2)$$

where $\mathcal{F}^{-1}\{\}$ represents the two-dimensional (2D) inverse Fourier transform operation, and λ and d are the recording wavelength and the distance of the hologram, respectively. By setting the location parameters (a, b) of the corresponding sub-holograms in the hologram plane,

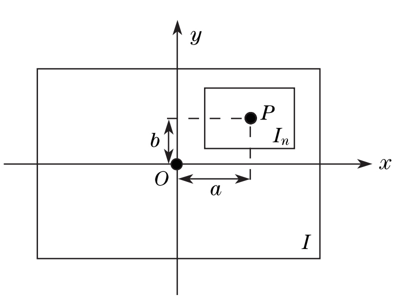

Fig. 1. Reconstruction coordinates of the synthetic aperture digital hologram.

the adjacent sub-holograms can be reconstructed with different splicing distances, and their the corresponding synthetic reconstruction images can be obtained.

The wavefronts of the reconstructed image fields will displace one another due to the splicing dislocation of sub-holograms. Therefore, the synthetic reconstruction image will become illegible, and the image quality will be degraded. With the numerical reconstruction method proposed above, for every two adjacent sub-holograms, we reconstruct these sub-holograms with different splicing distances and acquire the corresponding synthetic reconstruction images. With the assessment of the image variance[18], which should reach the maximum when the reconstructed image is clearest, accurate splicing distance between sub-holograms can be determined. Then, the accurate synthetic reconstruction image can be acquired with the superposition of all the reconstruction results of sub-holograms according to the identified splicing distances.

Figure 2 shows the experimental setup, which is analogous to a Mach-Zehnder interferometer. A USAF resolution test target is used as the recorded object. Two beams are obtained by dividing the laser (λ=532 nm) with a beam splitter. Then, the reference and object waves are generated by expanding and collimating the two beams, respectively. A black-white type CCD with $1\,626_{\mathrm{H}} \times 1\,236_{\mathrm{V}}$ (pixel) and pixel size of 4.4×4.4 (μm) is used for recording the digital hologram. In the hologram recording plane, the motion of CCD is controlled by a two-dimensional precision translation stage with resolution of 1.25 μm. In our design, the adjacent sub-holograms have no overlapping portions and the paraxial approximation is not satisfied during the hologram recording procedure. The horizontal and vertical translation intervals of the CCD target are 7 155 and 5 438.75 μm, respectively. The recording distance$d$ is chosen as 9.1 cm. Next, $3_{\mathrm{H}} \times 4_{\mathrm{V}}$ sub-holograms are recorded to compose the synthetic aperture digital hologram. To make the view field of the synthetic reconstruction image sufficiently large, every sub-hologram is padded to $5\,000_{\mathrm{H}} \times 5\,000_{\mathrm{V}}$ (pixel) with zeros elements during the numerical reconstruction procedure.

Figure 3 shows portion of the synthetic reconstruction image with a size of approximately 1×1 (mm). With the default splicing distance between the sub-holograms, the reconstructed images obtained by the Fresnel transform method, and the convolution approachs are shown in Figs. 3(a) and (b), respectively. Figures 3(a1) and (b1) are the magnified intensity image corresponding to the selected region in Figs. 3(a) and (b), respectively. With the same splicing dislocation between the sub-holograms, the quality of the reconstructed image obtained by the Fresnel transform method is lower than that obtained by the convolution approach due to the influence of the non-paraxial aberration. Figures 3(c) and (d) show the reconstructed images obtained by correcting the splicing dislocation between the sub-holograms with the Fresnel transform method and the convolution approach, respectively. Figures 3(c1) and (d1) are the magnified intensity images corresponding to the selected regions in Figs. 3(c) and (d), respectively. By adjusting the splicing distances between the sub-holograms with the convolution approach, the accurate splicing

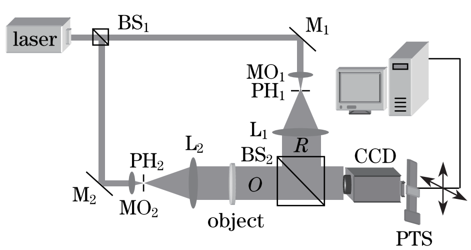

Fig. 2. Experimental setup for recording the synthetic aperture digital hologram. BS: beam splitters; M: mirrors; MO: microscope objective; PH: pinholes; L: lens; PTS: precision translation stage.

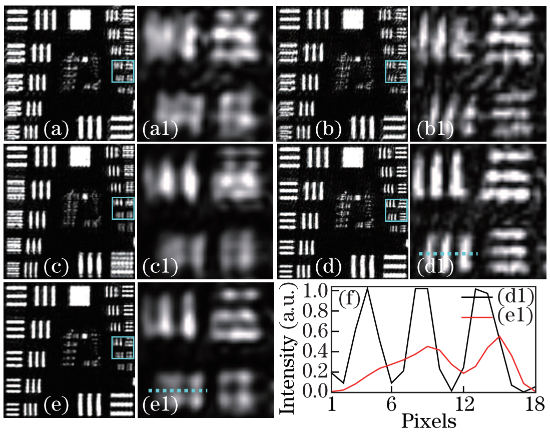

Fig. 3. (Color online) Reconstruction results of the synthetic aperture digital holographic image. (a), (b) Reconstructed images obtained with the default splicing distance of the sub-holograms by using the Fresnel transform method and the convolution approach, respectively; (c), (d) reconstructed images obtained by correcting the splicing dislocation of the sub-holograms with the Fresnel transform and the convolution approaches, respectively; (e) reconstruction result obtained by using the Fresnel transform method with the accurate splicing distance of sub-holograms (obtained by correcting the splicing dislocation of sub-holograms with the convolution approach); (a1)–(e1) magnifications of the marked areas in (a)–(e); (f) intensity distribution along the dashed line in (d1) and (e1).

distance can be determined by assessing the quality of the corresponding synthetic reconstruction images and the high-quality synthetic reconstruction image without non-paraxial aberration can be obtained. In contrast, by adjusting the splicing distances between the sub-holograms with the Fresnel transform method, the accurate splicing distance cannot be determined by assessing the quality of the corresponding synthetic reconstruction images because the quality of the reconstructed image is influenced by non-paraxial aberration, as well as by the splicing dislocation of the sub-holograms. Therefore, the synthetic reconstruction image is of low quality due to the influence of both the non-paraxial aberration and the inaccurate correction for the splicing dislocation between the sub-holograms. Figure 3(e) shows the reconstruction result obtained by using the Fresnel transform method with the accurate splicing distance between the sub-holograms (obtained by correcting the splicing dislocation between the sub-holograms with the convolution approach) and Fig. 3(e1) is the magnification of the marked area in Fig. 3(e). Figure 3(f) shows the intensity distribution along the dashed line in Figs. 3(d1) and (e1). Even with the accurate splicing distances of sub-holograms, the quality of the synthetic reconstruction image obtained with the Fresnel transform method is not ideal due to the influence of the non-paraxial aberration.

In conclusion, we propose a new correction method for the splicing dislocation of sub-holograms in synthetic aperture digital holography, in which the adjustment of the splicing distances between the sub-holograms is achieved with the convolution approach and the accurate splicing distance is determined by assessing the quality of the corresponding synthetic reconstruction images. This method can be used to avoid the non-paraxial aberration affecting the quality of the synthetic reconstruction image and therefore accurately correct the splicing dislocation between the sub-holograms when the paraxial approximation is not satisfied during the recording procedure of the synthetic aperture digital hologram. With this new method, accurate correction for the splicing dislocation between the sub-holograms is achieved and high-quality reconstructed images without non-paraxial aberration are obtained. This method provides a reasonable approach for implementing accurate synthesis of holographic reconstruction fields and has potential applications in synthetic aperture digital holography.

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