Improvement of speckle noise suppression in digital holography by rotating linear polarization state

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An improved polarization recording approach to reduce speckle noise in digital holography is proposed. Multiple off-axis holograms are obtained by rotating the linear polarization state of both illumination and reference wave simultaneously. By averaging the intensity fields, the speckle noise in the reconstructed images is well suppressed. Statistical evaluation of the experimental results shows the effectiveness and improvement of the proposed method.

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With the fast development of charge-coupled device (CCD) and computer science, holograms can be recorded and reconstructed numerically without photographic plates[1,2]. Owing to the prominent optical features and computational advantages of digital photography, it has been widely applied in many fields[3−5]. However, the quality of reconstructed images often suffers from speckle noise, which is due to the random interferences caused by the many lights scattered from different elements when a coherent light illuminates a relatively rough surface[6]. Thus, the elimination of speckle noise becomes a significant problem.

Great efforts involving the processes of recording and reconstruction have been made to reduce the speckle noise. Pedrini *et al.* decreased the coherence length of the illumination beam, but this weakened the quality of the reconstructed image[7]. Kim used wavelength-scanning digital holography to generate cross-sectional images, but this increased system complexity[8]. Digital signal processing technique is often adopted to remove speckle content. Garcia-Sucerquia *et al.* employed median filter, which led to a loss of detail[9]. Mirza *et al.* implemented image preprocessing and wavelet filters[10]. Maycock *et al.* brought forward a method of discrete Fourier filtering[11]. Moreover, superposing multiplespeckle patterns was proven effectively in diminishing speckle noise. Kang obtained a set of multiple holograms by rotating the illuminating light continuously; however, the rotating range is severely limited[12]. Nomura *et al.* recorded holograms with a light source of multiple wavelengths[13]. Rong *et al.* presented a way of generating multiple holograms using a circularly polarized illumination wave and rotating the linearly polarized reference wave, and reduced speckle noise by averaging the corresponding intensity fields[14]. However, only the projection component of the illumination wave interferes with the reference wave. The incoherent background formed by the remainder of the projection may also decrease the utilization rate of the dynamic range for CCD and debase the signal-to-noise ratio (SNR). Furthermore, the speckle patterns of the holograms are

correlated, which would degrade the final result.

With the method proposed by Rong *et al.*, the object wave field remains unchanged. In this letter, we introduce an improved method to decrease the effects of speckle noise in digital holography. Both the illumination and reference waves are uniformly linear polarized in the parallel direction, and the multiple off-axis holograms are generated simply by rotating the polarization plane simultaneously through different angles. A series of intensity images with different speckle patterns is reconstructed by Fresnel reconstruction algorithm after the process of frequency filtering and inverse Fourier transform in order to repress zero-order and twin image effects[15]. By recording different linear polarization directions and averaging the reconstructed images, similar to some extent to incoherent illumination, the speckle noise can be considerably suppressed without decreasing the resolution.

The experimental setup is illustrated in Fig. 1. A frequency-doubled Nd:YAG laser (532 nm, 20 mW) is used as light source. A polarized beam splitter (PBS) is adopted to split the illumination beam and the reference beam. Two half-wave plates (HWP2 and HWP3) are rotated to obtain the same linear polarization state, and HWP1 is applied to adjust the intensity ratio of the illumination beam to the reference beam. Both beams
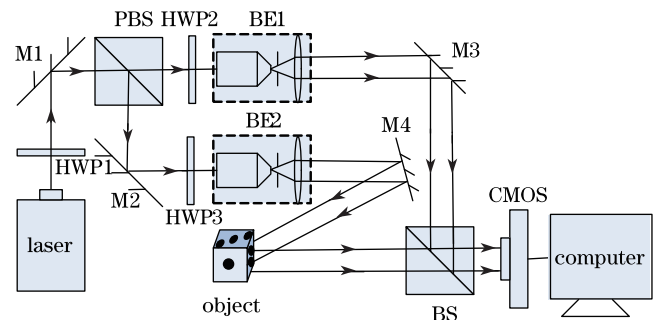

Fig. 1. Schematic diagram of experimental setup. M1, M2, M3, M4: mirrors; BE1, BE2: optical beam expanders; L1, L2: lens; BS: beam splitter.

are collimated as plane waves by beam expanders (BEs), which are composed of spatial filters and collimating lens. A complementary metal oxide semiconductor (CMOS) camera is used to record holograms with pixel array of 1024×1024 and a pixel pitch of 6.7×6.7 (μm). The object is a cubic dice with a width of about 10 mm, located at a distance of 305 mm from the recording plane. The illumination and reference beam polarizations are rotated synchronously by $4°$ each time and then the off-axis holograms are recorded individually.

Figure 2(a) gives a cutout of 535×535 (pixels) from the reconstructed intensity image obtained by single hologram; the image is blurred by speckle noise. Figures 2(b) and (c) show the averaged reconstructed images of multiple polarization holograms; the number of holograms in the averaging process is Fig. 2(b) 4 and Fig. 2(c) 16, respectively. In addition, Figs. 2(d)–(f) are the corresponding partial magnified images for a uniform region A of Figs. 2(a)–(c), with dimensions of 90×90 (pixels). The speckle noise is well suppressed and the definition of the intensity reconstructed image is improved with the use of an increased number of holograms.

Meanwhile, in first-order statistical properties of speckle patterns, contrast C is frequently discussed as an effect of speckle noise[16], which is defined by

$$C = \frac{\sigma_{\mathrm{I}}}{\overline{I}}, \tag{1}$$

where σ_{I} is the standard deviation of the intensity field and $\overline{I} = \sum_{i=1}^{n}\sum_{j=1}^{m} I(i,j)/(n\times m)$, $\sigma_{\mathrm{I}} = \{\sum_{i=1}^{n}\sum_{j=1}^{m}\left[I(i,j)-\overline{I}\right]^2/(n\times m-1)\}^{1/2}$, $n\times m$ is the size of the target region, i is for the row, and j is for the column. Assuming the sum of N independent speckle patterns with equal mean intensities, the contrast falls in proportion to $1/\sqrt{N}$ as N increases, and the SNR rises correspondingly as $\sqrt{N}$[16]. The dotted line in Fig. 3 presents the contrast value of a uniform region B with a size of 50×50 (pixels) as indicated in Fig. 2(a). The contrast value drops drastically as the number of hologram increases. Compared with the theoretical condition that all these speckle patterns are uncorrelated with one another, as represented by the solid

Fig. 3. Contrast value of reconstructed intensity images versus number of holograms.

regression line, the experimental result does not decrease strictly in proportion to $1/\sqrt{N}$. The inconformity between the two lines is due to the weak correlation between different intensity images.

For further discussion of the correlation of different speckle patterns obtained under different polarization conditions, Fig. 4(a) describes the correlation coefficients between every two reconstructed images[17]. Furthermore, Fig. 4(b) shows the correlation coefficients between

Fig. 4. (a) 3D plot of correlation coefficients between every two reconstructed images with the total ordinal number of 25; (b) correlation coefficients between the zero degree reconstructed image and other reconstructed images obtained by rotating 4 degrees of the polarization state each time.
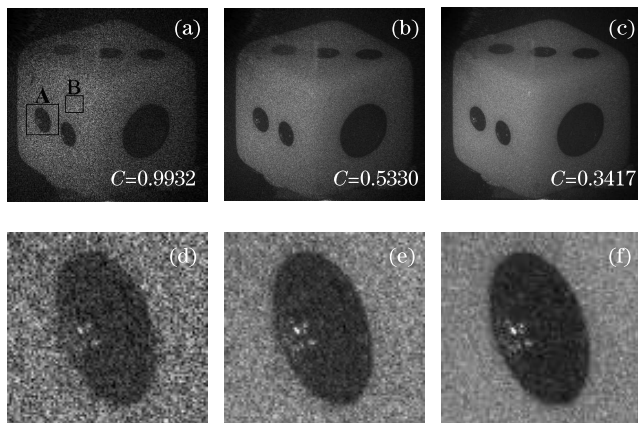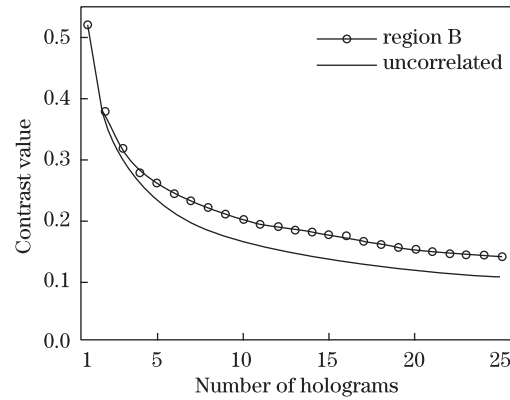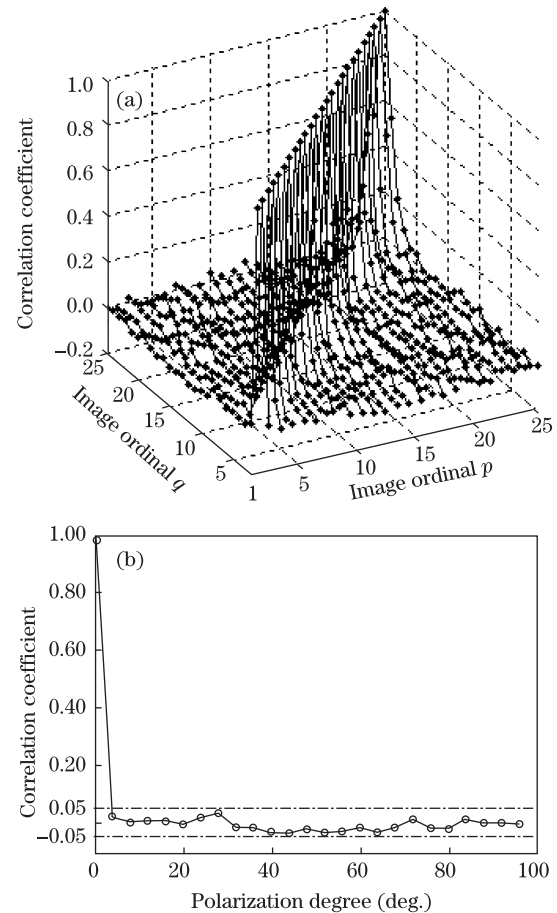

Fig. 2. Reconstructed intensity images obtained by (a) 1 hologram; (b) 4 holograms; (c) 16 holograms; (d)–(f) corresponding partial magnified images of region A of (a)–(c).

the first reconstructed image, at zero degree, and each of the 25 reconstructed images at different polarization states. The self-correlation coefficient of the first image is equal to 1, and the correlation coefficients between the other images are close to zero, as expected. In comparison with the work of Rong *et al.*[14], the correlation coefficient is no longer related to the rotation angle of the polarization state with the technique proposed in this letter.

In conclusion, an improved technique based on linear polarization is presented to reduce speckle noise in digital holography. Multiple holograms are obtained by rotating the uniformly linear polarized illumination wave and the reference wave simultaneously. The principle of the method and the experimental results are interpreted. Numerical evaluation indicates the effectiveness of the proposed approach.

References

1. J. W. Goodman and R. W. Lawrence, Appl. Phys. Lett. **11,** 77 (1967).
2. U. Schnars and W. Jüptner, Appl. Opt. **33,** 179 (1994).
3. F. Charrière, J. Kuhn, T. Colomb, F. Montfort, E. Cuche, Y. Emery, K. Weible, P. Marquet, and C. Depeursinge, Appl. Opt. **45,** 829 (2006).
4. N. Demoli, Opt. Express **14,** 2117 (2006).
5. F. Dubois, N. Callens, C. Yourassowsky, M. Hoyos, P. Kurowski, and O. Monnom, Appl. Opt. **45,** 864 (2006).
6. J. C. Dainty, *Laser Speckle and Related Phenomena* (Springer Verlag, Berlin, 1984).
7. G. Pedrini and S. Schedin, Optik (Jena) **112,** 427 (2001).
8. M. K. Kim, Opt. Express **7,** 305 (2000).
9. J. Garcia-Sucerquia, J. A. H. Ramirez, and D. V. Prieto, Optik (Stuttgart) **116,** 44 (2005).
10. S. Mirza, R. Kumar, and C. Shakher, Opt. Eng. **44,** 045603 (2005).
11. J. Maycock, B. M. Hennelly, J. B. McDonald, Y. Frauel, A. Castro, B. Javidi, and T. J. Naughton, J. Opt. Soc. Am. A **24,** 1617 (2007).
12. X. Kang, Chin. Opt. Lett. **6,** 100 (2008).
13. T. Nomura, M. Okamura, E. Nitanai, and T. Numata, Appl. Opt. **47,** D38 (2008).
14. L. Rong, W. Xiao, F. Pan, S. Liu, and R. Li, Chin. Opt. Lett. **8,** 653 (2010).
15. T. Kreis, *Handbook of Holographic Interferometry: Optical and Digital Methods* (Wiley-VCH, Weinheim, 2005).
16. J. W. Goodman, *Speckle Phenomena in Optics: Theory and Applications* (Roberts and Co., Englewood, 2006).
17. R. C. Gonzalez and R. E. Woods, *Digital Image Processing* (2nd edition) (Prentice Hall, New Jersey, 2002).