An effective method for reducing speckle noise in digital holography

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An effective method for reducing the speckle noise in digital holography is proposed in this paper. Different from the methods based on classical filtering technique, it utilizes the multiple holograms which are generated by rotating the illuminating light continuously. The intensity images reconstructed by a series of holograms generated by rotating the illuminating light possess different speckle patterns. Hence by properly averaging the reconstructed intensity fields, the speckle noises can be reduced greatly. Experimental results show that the proposed method is simple and effective to reduce speckle noise in digital holography.

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Recent development in charge-coupled devices (CCDs) and digital computers have made it possible to record a hologram using a CCD camera and reconstruct the object wavefront numerically. This has led to the development of digital holography. Compared with conventional holography, digital holography has the advantage that the amplitude as well as the phase information of the object wavefront can be obtained quantitatively and analyzed digitally without the need for wet chemical processing. However, digital holography possesses drawbacks which are similar to those of conventional holography such as the presence of speckle noise due to the roughness of object surface. Moreover, speckle noise in digital holography has more overwhelming effects than that of conventional holography.

Great effort has been focused on removing the speckle noise in digital holography[1−9] and speckle interferometry[10−15]. Garcia-Sucerquia *et al.*[1] presented an effective method to reduce the speckle noise in reconstructed image. This method is based on resizing (minishing) the reconstructed image together with median filtering. Morimoto *et al.*[2] used the divided holograms to decrease the effect of speckle noise in deformation measurement by phase-shifting digital holography. They divided the original full-size hologram into 16 small holograms. Each small hologram is pasted at the original position on the full-size hologram with null data at the other pixels. By searching the maximum average amplitude among the 16 reconstructed wavefronts before and after deformation at each pixel, the phase value at this pixel corresponding to the deformation is determined. Recently, an effective method based on multiple holograms[3,4] is used to reduce the speckle noise in reconstruction of digital holography. Baumbach *et al.*[3] generated multiple holograms by a set of different lateral positions of a CCD camera which is used to record the holograms. They utilized the shift theorem of Fourier transform to reduce the speckle noise which can be interpreted as generation of a large synthetic aperture consisting of many small apertures given by a single CCD. Kebbel *et al.*[4] obtained multiple holograms by moving continuously a diffusing screen perpendicular to the optical axis of a CCD sensor. By properly averaging several phase images with different speckle patterns, they improved drastically the accuracy of the phase measurement.

In this paper, a method based on multiple holograms to reduce the speckle noise in digital holography is presented. However, the multiple holograms are generated by rotating an illuminating beam through different angles. This is different from the above-mentioned methods[3,4]. A series of off-axis Fresnel holograms of a same object are captured. By properly averaging the reconstructed intensity images, the speckle noise can be suppressed drastically.

It is known that the effect of speckle noise in laser interferometry can be measured using the contrast value of a speckle pattern. The higher the contrast value is, the more significant the effect of speckle noise will be. The contrast of a speckle pattern is defined as

$$\nu = \frac{\sigma}{\langle I \rangle}, \tag{1}$$

where $\langle I \rangle = \sum_i \sum_j I(i,j)/(n \times m)$ is the mean value of intensity I of a speckle pattern, $n \times m$ is the size of the speckle pattern, and $\sigma = \left(\sum_i \sum_j \left(I(i,j) - \langle I \rangle \right)^2 / (n \times m - 1) \right)^{1/2}$ is the standard deviation of intensity of speckle pattern. For a standard interferometric speckle pattern, its intensity presents a distribution of negative exponent. Hence the contrast value for a standard speckle pattern is always equal to 1.

Assuming that $I_1, I_2, \cdots, I_p$ represent a series of speckle patterns (p is the number of speckle patterns) and follow the same intensity distribution but are statistically independent of each other, we have

$$\left\langle \hat{I} \right\rangle = \langle I_i \rangle, \tag{2}$$

where $\left\langle \hat{I} \right\rangle$ is the mean value of $\hat{I}$ and $\hat{I} = \frac{1}{p} \sum_{i=1}^{p} I_i$, while $\langle I_i \rangle$ is the mean value of any speckle pattern I_i. In addition, we have

$$\hat{\sigma} = p^{-1/2}\sigma_i, \tag{3}$$

where $\hat{\sigma}$ and σ_i are respectively the standard deviations of $\hat{I}$ and I_i. Combining Eqs. (1)—(3), the contrast value of the averaged speckle pattern $\hat{I}$ can be deduced as

$$\hat{\nu} = \frac{\hat{\sigma}}{\left\langle \hat{I} \right\rangle} = p^{-1/2}\nu_i, \tag{4}$$

where $\nu_i = \sigma_i/\langle I_i \rangle$ is the contrast value of I_i. It can be seen that the contrast value of the averaged p speckle patterns is decreased by a factor of $p^{-1/2}$ compared with that of a single speckle pattern. Hence the devastating effect of speckle noise can be significantly reduced by properly averaging a number of speckle patterns that do not correlate with each other.

In holography, the hologram is formed by the interference between object and reference waves. Hence different incidence angles of illuminating beam will generate holograms with different fringe patterns. The reconstructed images by these different holograms will possess different speckle patterns. Hence by properly averaging the reconstructed intensity images, the speckle noise can be reduced effectively. In fact, the use of averaging multiple speckle patterns in reduction of speckle noise can be found in early coherent imaging systems[10]. In Ref. [10], the authors introduced a random vibration (100 − 1000 Hz) to the generated different spackle patterns so that they could observe directly the time-averaged image on a screen, not like the process in digital holography which needs first the intensity reconstruction for every hologram before carrying out the averaging algorithm.

Figure 1 shows the schematic of experimental setup for recording an off-axis Fresnel digital hologram. A 50-mW He-Ne laser beam ($\lambda = 632.8$ nm) is divided by a polarization beam splitter (PBS) into illumination and reference beams. The reference beam is converted to a plane wave by use of a beam expander consisting of a pinhole for spatial filtering and a lens for collimating, and is directed at the CCD sensor through a mirror and a beam splitter (BS). A polarizer in front of the beam expander is used to control the intensity of the reference wave. The illuminating beam is directed at an object through a rotational mirror (RM). The tested object is a battery which is measured about 4.7 cm long and 1.3 cm in diameter. A series of holograms with a recording distance of 570 mm were obtained at different rotation angles of RM. The CCD camera used in the experiment is Pulnix TM-1402. The pixel size of CCD sensor is 4.65×4.65 (μm) and the pixel number used is 1024×1024. Off-axis holograms were obtained with the reference wave inclined at an incidence angle θ and the object wave propagating perpendicular to the CCD sensor surface. Since the CCD sensor possesses a relatively low spatial resolution, the incidence angle θ should not exceed a maximum value ($\theta_{\max}$) for which the carrier frequency of the interferogram is equal to the Nyquist frequency of the detector. $\theta_{\max}$ is given by

$$\theta_{\max} = \frac{\lambda}{2\Delta x}, \tag{5}$$

where λ is the wavelength of the laser beam and Δx is the pixel size of the CCD sensor. The value of $\theta_{\max}$ in the present experimental setup is calculated as 3.90°.

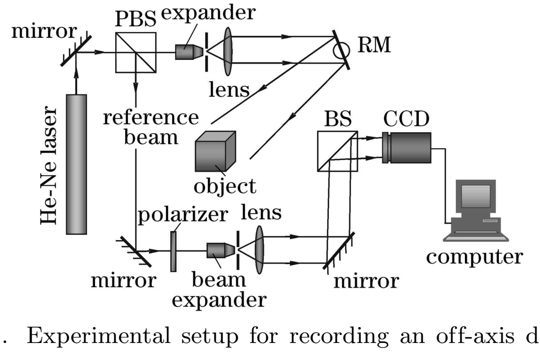

Fig. 1. Experimental setup for recording an off-axis digital hologram.

Figure 2 shows a hologram of the battery captured using the setup. Figure 3 shows the intensity images reconstructed using Fresnel transform algorithm based on multiple holograms. The numbers of holograms used for the intensity reconstruction are respectively 1, 4, 8, and 12. It can be seen from Fig. 3(a) that the speckle noise overlaid the whole reconstructed image and the battery could not be viewed clearly. However, by properly averaging the multiple reconstructed intensity images, the speckle noise is suppressed and the visibility is improved

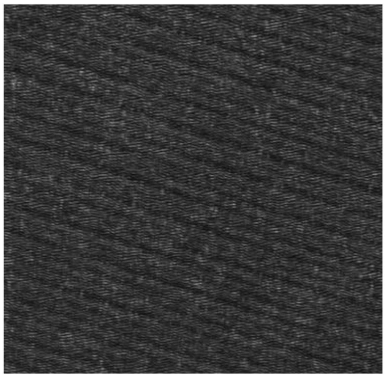

Fig. 2. Recorded hologram of a battery.

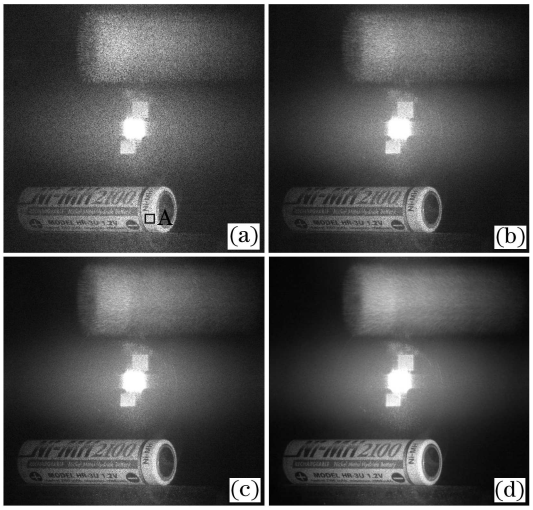

Fig. 3. Reconstructed images of a battery obtained by (a) single hologram; (b) 4 holograms; (c) 8 holograms; (d) 12 holograms.

effectively. The more holograms are used, the clearer the reconstructed image is. In addition, because the holograms are obtained using illuminating light with different directions, the direct superposing of the reconstructed wavefronts obtained using these holograms can result in additory fringes. Hence, in this paper, the reconstructed intensity fields (not the reconstructed wavefronts) is averaged to reduce the speckle noise. Similarly, averaging the reconstructed wavefronts is not adopted to evaluate the phase field. Another question is that there are two white squares near the zero-order diffraction as can be seen in Fig. 3. This phenomenon may result from some other light which reaches the CCD target and mixes with the object wave and illuminating wave to form a hologram. Then when we perform the reconstruction, this unnamed light recurs as seen in the reconstructed images.

Figure 4 shows the corresponding distributions of the relative deviations δ obtained using the equation $\delta(i,j) = (I(i,j) - \langle I \rangle) / \langle I \rangle$ on a region Marked "A" in Fig. 3(a). We can see that the relative deviation decreases with increasing the number of holograms. This shows again that the speckle noise is significantly reduced by the multiple holograms. Figure 5 shows the contrast values of reconstructed intensity fields versus the number of holograms used for reconstruction. The contrast values are also calculated from region A. We can see from Fig. 5 that the contrast value of reconstructed image by a single hologram is not exactly equal to 1. This indicates that the speckle pattern formed by reconstruction of a single hologram is not a standard one. It is also seen that the contrast values decrease drastically at the first and then decrease at a lower rate with increasing number of holograms. This phenomenon seems coincident with Eq. (4) which presents a variation of contrast values according to $p^{-1/2}$. However, in fact the contrast values do not strictly vary according to $p^{-1/2}$ because of the partial correlation between the reconstructed intensity images obtained by every single hologram. This can be seen in Fig. 6 which shows the distribution of correlation coefficients evaluated by the relationship between the reconstructed intensity fields by every single hologram:

$$C_{p,q} = \frac{\sum_{i}^{n}\sum_{j}^{m}\left[\left(I^{p}(i,j) - \langle I^{p}\rangle\right)\left(I^{q}(i,j) - \langle I^{q}\rangle\right)\right]}{\left[\sum_{i}^{n}\sum_{j}^{m}\left(I^{p}(i,j) - \langle I^{p}\rangle\right)^{2}\sum_{i}^{n}\sum_{j}^{m}\left(I^{q}(i,j) - \langle I^{q}\rangle\right)^{2}\right]^{1/2}}, \quad (6)$$

where p and q represent the image pair to correlate. $p = 1, 2, 3, \cdots, 12$, $q = 1, 2, 3, \cdots, 12$. $C_{p,q}$ is the correlation coefficient of the considered image pair ($c_{p \cdot q} \in [-1, 1]$). n and m are the sizes of images in pixel. i represents the row and j represents the column. $\langle I^{p}\rangle$ and $\langle I^{q}\rangle$ are the average values of intensity images I^{p} and I^{q}. The total number of the reconstructed images in our experiment is 12 (More holograms can be captured so long as the test object is within the illuminating field).

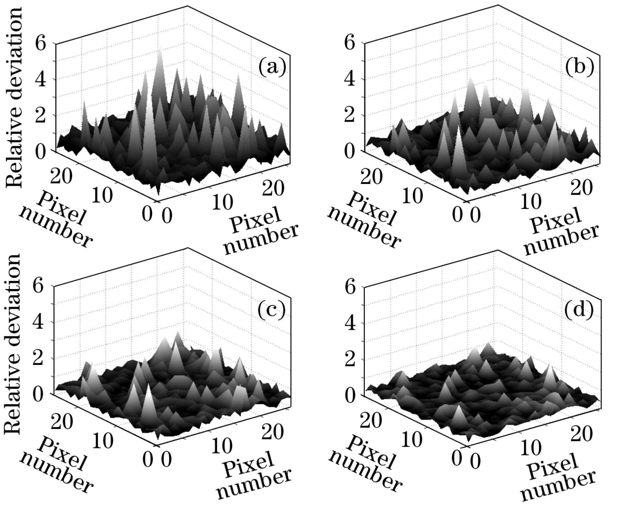

Fig. 4. Distributions of the relative deviations corresponding to Figs. 3(a)—(d) for region A indicated in Fig. 3(a).

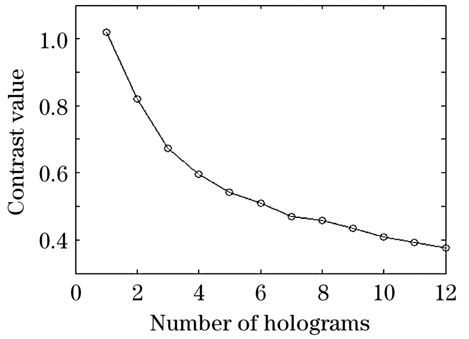

Fig. 5. Contrast values from region A in reconstructed intensity images versus the number of holograms used.

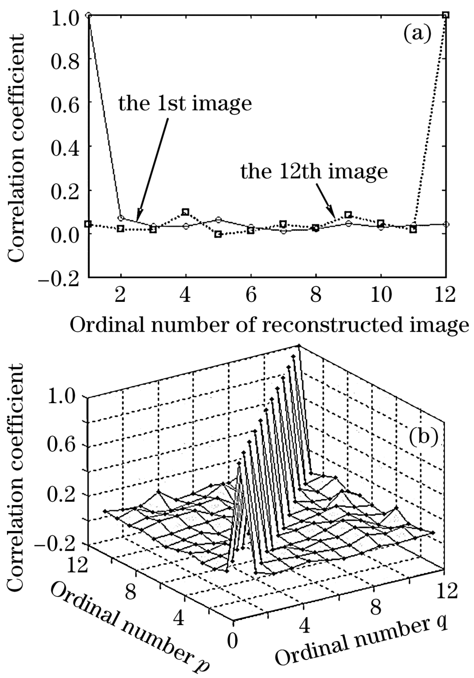

Fig. 6. (a) 2D plot of correlation coefficients between the 1st, 12th reconstructed images respectively and the other 11 reconstructed images. (b) 3D plot of the correlation coefficients between every pair of reconstructed images (total number of reconstructed images is 12).

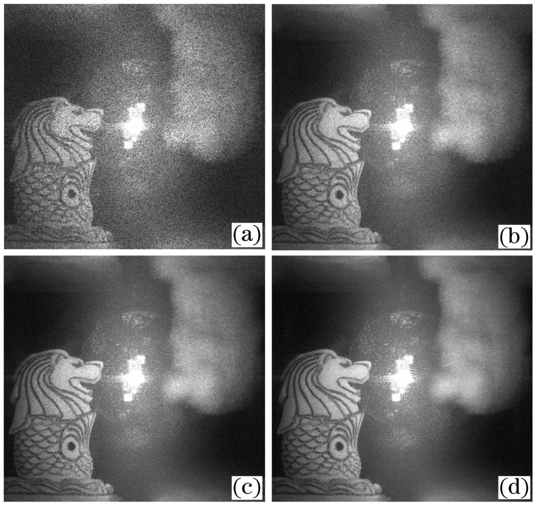

Fig. 7. Reconstructed images of a sculpture obtained by (a) single hologram; (b) 5 holograms; (c) 10 holograms; (d) 15 holograms.

Figure 6(a) shows a two-dimensional (2D) plot of correlation coefficients between the 1st, 12th reconstructed intensity images respectively and the other 11 reconstructed intensity images. Figure 6(b) shows a three-dimensional (3D) plot of correlation coefficients between every pair of the 12 reconstructed images. It can be seen from Fig. 6 that the reconstructed images by every single hologram are partial correlative, and the correlation coefficients are distributed random around 0 but not exactly equal to 0. In addition, a ridge in Fig. 6(b) which represents the self-correlation coefficient of the reconstructed images has a constant value of 1.

Figure 7 shows the experimental results of another specimen. The test object is a merlion sculpture measured about 4.3 cm high and 2.5 cm in diameter. The numbers of holograms used for the intensity reconstruction are respectively 1, 5, 10, and 15. It can be seen once more that the proposed method is an effective approach in speckle noise reduction in digital holography.

In conclusion, the speckle noise in digital holography can be reduced effectively by using multiple holograms which are obtained by rotating the illuminating beam continuously. The experimental results on a battery and a sculpture show that the presented approach can be used conveniently to decrease speckle noise in intensity reconstruction in digital holography.

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References

1. J. Garcia-Sucerquia, J. A. H. Ramírez, and D. V. Prieto, Optik **116,** 44 (2005).
2. Y. Morimoto, T. Nomura, M. Fujigaki, S. Yoneyama, and I. Takahashi, Exp. Mech. **45,** 65 (2005).
3. T. Baumbach, E. Kolenovic, V. Kebbel, and W. Jüptner, Appl. Opt. **45,** 6077 (2006).
4. V. Kebbel, J. Mueller, and W. P. O. Jueptner, Proc. SPIE **4778,** 188 (2002).
5. F. Wyrowski and O. Bryngdahl, J. Opt. Soc. Am. A **6,** 1171 (1989).
6. J. Maycock, C. P. McElhinney, J. B. McDonald, T. J. Naughton, B. M. Hennelly, and B. Javidi, Proc. SPIE, **6187,** 618716 (2006).
7. G. H. Kaufmann and G. E. Galizzi, Opt. Eng. **35,** 9 (1996).
8. B. Kemper, A. Höink, D. Carl, and G. von Bally, Proc. SPIE **6341,** 634125 (2006).
9. N. Bertaux, Y. Frauel, P. Réfrégier, and B. Javidi, J. Opt. Soc. Am. A **21,** 2283 (2004).
10. Z. Chen, J. Li, and Y. Chen, Chin. J. Lasers (in Chinese) **12,** 726 (1984).
11. K. Greath, Opt. Lett. **10,** 582 (1985).
12. J. Kauffmann, M. Gahr, and H. J. Tiziani, Proc. SPIE, **4933,** 9 (2003).
13. S. Mirza, R. Kumar, and C. Shakher, Opt. Eng. **44,** 045603 (2005).
14. A. Capanni, L. Pezzati, D. Bertani, M. Cetica, and F. Francini, Opt. Eng. **36,** 2466 (1997).
15. C. Shakher, R. Kumar, S. K. Singh, and S. A. Kazmi, Opt. Eng. **41,** 176 (2002).