Speckle noise reduction in digital holography by use of multiple polarization holograms

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A novel speckle reduction technique for digital holography is proposed. Multiple off-axis holograms are recorded using a circularly polarized illumination beam and a rotating linearly polarized reference beam. The speckle noise in the reconstructed images is suppressed by averaging these fields. We demonstrate the effectiveness of this technique experimentally and conduct additional statistical evaluation.

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In digital holography, cameras like charge-coupled device (CCD) or complementary metal-oxide semiconductor (CMOS) are used to record holograms, and object wavefronts are reconstructed computationally by simulating the propagation of the complex amplitudes of optical beams[1]. Despite its advantages, digital holography also possesses drawbacks similar to that of most coherent methods, such as speckle noise arising from the roughness of the object surface when height variations exceed light wavelengths[2]. When a coherent light beam illuminates the rough surfaces of randomly scattering objects, the waves scattered by different surface points fluctuate statistically because of height variations. The superposition of these scattered waves forms a stationary speckle pattern in the recording plane[3]. Thus, the hologram not only includes the grating structure of the light filed in object plane, it also incorporates speckles. The presence of speckle noise in reconstructed images degrades the image resolution and measurement accuracy[4].

Various experimental and computational methods have been presented to minimize such drawbacks[5−8]. One approach was to utilize multiple reconstructed images with different speckle patterns. Kebbel *et al*. generated a series of holograms by continuously spinning a diffuser perpendicular to the optical axis of CCD, but the approach was not applicable to opaque objects[9]. Nomura *et al*. obtained multiple holograms using a tunable coherent light source, but these increased the complexity of the system[10]. Quan *et al*. obtained multiple off-axis Fresnel holograms by changing the incident angle of illumination beam through a rotating mirror, which was limited to the rotation range of the mirror and only suitable for small samples[11,12].

In this letter, we present a novel method of generating multiple holograms to suppress speckle noise in digital holography. We do not vary the incident angle of the illumination beam or the relative position between the object and the camera. Instead, we utilize multiple off-axis holograms using the circularly polarized illumination beam and multiple settings for the linear polarization plane of the reference beam.

When circularly or elliptically polarized light interferes with linearly polarized light, only the projection component of the former interferes with the latter; the remainder of the projection is viewed as incoherent background. Although only the information of some polarized status can be recorded at one time just like the traditional recording procedures of two linearly polarized beams, the information of the other polarization component can latterly be obtained by rotating the polarization of reference beam during the recording process.

Then, the holograms were processed by frequency filtering and inverse Fourier transform to suppress zero-order and twin image effects[4]. Magnified real images were reconstructed by Fresnel reconstruction algorithm[4]. A set of reconstructed intensity images with different speckle patterns was obtained. By averaging the images, the speckle noise was suppressed considerably. The experimental result and statistical evaluation were used to confirm the effectiveness of the proposed method.

The experimental setup is illustrated in Fig. 1. A solid-state laser with a power of 20 mW and a wavelength of 532 nm was used as light source. A polarized beam splitter (PBS) and two half-wave plates (HWPs) were used to split and adjust the intensity ratio of the illumination beam and reference beam. By orienting the crystal axis of a quarter-wave plate (QWP) at 45° to an incident linear-polarized wave, the circularly polarized illumination beam was obtained. Meanwhile, by rotating the HWP, the polarization state of the reference beam was changed. Both beams were collimated as plane waves by beam expanders (BEs)

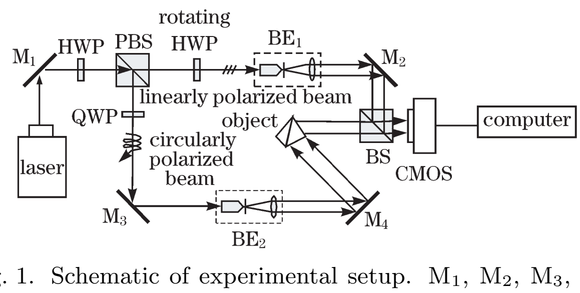

Fig. 1. Schematic of experimental setup. M_1, M_2, M_3, and M_4: mirrors; BS: beam splitter.

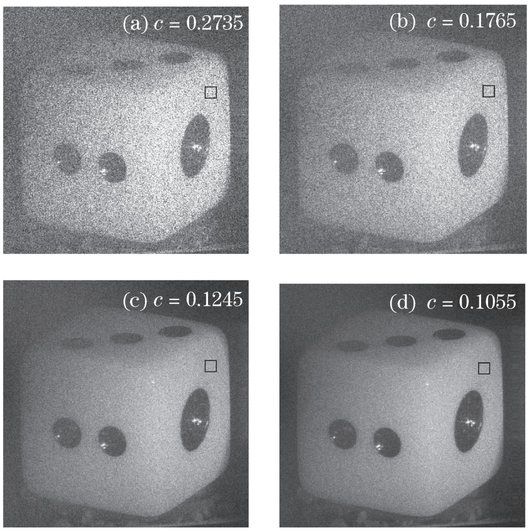

Fig. 2. Reconstructed images obtained by averaging of (a) 1 hologram; (b) 3 holograms; (c) 9 holograms; (d) 18 holograms.

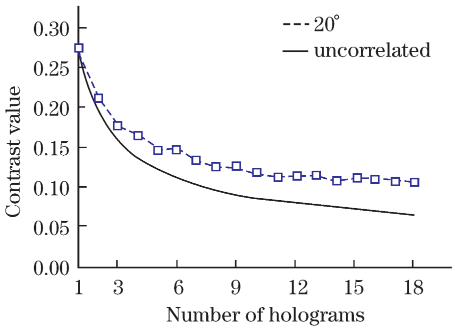

Fig. 3. Contrast values of reconstructed intensity by rotating 20° of polarization state each time versus the number of averaging holograms.

(i.e., BE_1 and BE_2 consisting of microscope objectives, pinholes as spatial filters, and collimating lenses). A CMOS camera with a pixel array of 1024×1024 pixels and a pixel pitch of 6.7 ×6.7 (μm) was used to record the off-axis holograms. A cubic dice with width of 10 mm was used as the object and was placed 492 mm away from the CMOS.

The effect of speckle noise in digital holography was evaluated by contrasting the speckle pattern[1]. Higher contrast indicated larger speckle noise. 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, i is for row and j is for column, $n \times m$ is the calculation window of the speckle pattern, and $\sigma = \sqrt{\sum_i \sum_j [I(i,j) - \langle I \rangle]^2/(n \times m - 1)}$ is the standard deviation of intensity[13].

Figure 2(a) shows an enlarged cutout (730×730 pixels) from the reconstructed intensity image using a single hologram. The image was blurred by speckle noise. The overall result after the averaging process is shown in Figs. 2(b)−(d). The rotation angle of the reference polarization was 20°. The number N of holograms used for reconstruction is 3, 9, and 18 for Figs. 2(b)−(d), respectively. Improvements in speckle noise suppression using multiple holograms, compared with the single hologram in Fig. 2(a), were clearly visible and computable in relation to the contrast value c of a uniform region in Fig. 2. The clarity of the synthesized images improved initially with the number of holograms; at a certain point onward, the information content of the object wave was exhausted, and further averaging only improved the image marginally.

Figure 3 shows the contrast value of a uniform region in Fig. 2 versus the number of holograms used in the averaging process. The dotted line represents the measured values when the rotating angle is 20° (Eq. (1)). The values decreased considerably for the first few holograms but at a lesser extent for higher N. For comparison, we incorporated into the solid line to represent the function proportional to $1/\sqrt{N}$. If a set of N uncorrelated speckle patterns are added for intensity purposes, the contrast falls in proportion to $1/\sqrt{N}$[3]. The inconformity between the two regression lines can be interpreted in terms of the partial correlation between the patterns of different polarized angles[2].

Figure 4 shows the correlation coefficient between the reconstructed zero-degree image and other images at different polarized states, all of which were recorded by rotating the reference beam at 4° each time and then reconstructed individually. The correlation coefficient between these reconstructed images can be expressed as[13]

$$c_{p,g} = \frac{\sum_i^n \sum_j^m [I^p(i,j) - \langle I^p \rangle][I^q(i,j) - \langle I^q \rangle]}{\sqrt{\sum_i^n \sum_j^m [I^p(i,j) - \langle I^p \rangle]^2 \cdot \sum_i^n \sum_j^m [I^q(i,j) - \langle I^q \rangle]^2}}, \tag{2}$$

where $c_{p,g} \in [-1, 1]$, p and q are the two images to be correlated, $\langle I^p \rangle$ is the average irradiance of the image p, and $\langle I^q \rangle$ is the average value of image q.

If the speckle patterns had not been correlated with each other, the correlation coefficient was supposed to be zero. Positive or negative coefficients indicate the relationship between images p and q. As the values for I^p increased, the values for I^q either increased or decreased. Figure 4 shows that the correlation coefficients are partially correlated due to the incoherent background. It is the reason why the distribution of contrast values, as shown in Fig. 3, does not coincide with that of uncorrelated patterns. Figure 4 further shows that when the polarization state of the reference beam is rotated by a multiple of $\alpha = 30°$, the correlation coefficient is at the minimum. Additionally, while α is used as a function of this object, for other objects, a different amount is required to obtain the correlation coefficient. This is determined

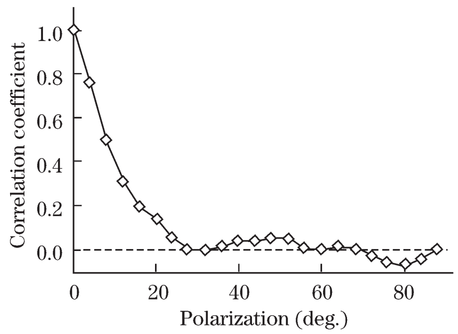

Fig. 4. Correlation coefficients between the zero-degree reconstructed images and other reconstructed images.

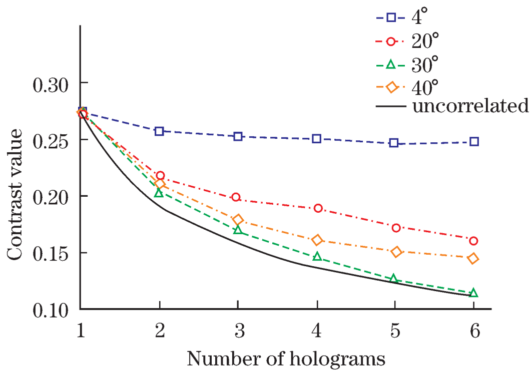

Fig. 5. Contrast value of averaging holograms by different rotation angles of polarization state.

by several factors, such as the translated distance of the surface, exact geometry, and size of the speckles[2].

We compared the contrast values of the synthesized images (Fig. 5). As opposed to Fig. 3, the polarization state of the reference beam rotates in different angles at each cycle. The solid line represents the contrast distribution of uncorrelated patterns while the dashed lines indicate the measured values when the reference beam is rotated by 4°, 20°, 30°, and 40°. The graph shows that for the same number of holograms, the speckle noise is most suppressed in the reference beam rotated in 30° steps. The speckle patterns on these reconstructed images can be regarded as uncorrelated with each other.

In conclusion, a novel method for speckle noise reduction based on the averaged intensity field is presented. The proposed method obtains multiple holograms upon rotation of the linearly polarized reference beam; simultaneously, a circularly polarized illumination beam is projected on the object. Both experimental results and statistical evaluations demonstrate that the improvement in speckle noise suppression depends on both the number of averaged holograms and the rotating angle of polarization. This approach is easy to manipulate and especially suitable for applications wherein the setup position and incidence direction cannot be changed.

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