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Two-step phase-shifting Fresnel incoherent correlation holography based on discrete wavelet transform*

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Fresnel incoherent correlation holography (FINCH) has the ability to generate three-dimensional images with a super-resolution by using incoherent sources. However, there are unwanted direct current term and twin image in interferograms, so it is of great significance to find a method to eliminate them. Phase-shifting technology is a most widely used technique for this task, but its three-step phase-shifting is not suitable for the instantaneous measurement of dynamic objects, and the quality of reconstructed image with the traditional two-step phase-shifting is lower. In this paper, we present a method of enhancing the resolution through using a two-step phase-shifting technology based on the discrete wavelet transform. After two-step phase-shifting, the resulting hologram is a superposition of multiple forms. The frequency of the resulting hologram is decomposed into different levels through using discrete wavelet transform, then the image is reconstructed after retrieving the low frequency band. Various experiments have verified the effectiveness of this method.

Keywords: holography, phase-shifting, wavelet transform

PACS: 42.40.Lx, 42.30.Va **DOI:** 10.1088/1674-1056/abab7d

1. Introduction

Using advanced computers and photonic devices, digital holography (DH) can record the hologram of a real three-dimensional (3D) object on a two-dimensional (2D) plane and reconstruct an image digitally.[1–4] However, in a coherent holography system, laser light is necessary for the holographic recording, which leads to speckle. The unavoidable coherent noise significantly constrains optical configurations.[5] The incoherent holography can alleviate this limitation by using spatially incoherent light and a properly designed interferometer.[6,7] Therefore, the incoherent digital holography technology has been increasingly developed.[8–12]

Fresnel incoherent correlation holography (FINCH) originally proposed by Rosen and Brooker[13,14] has developed rapidly and extensively in the field of imaging.[15–20] The FINCH presents a factor of about 1.5 in resolution higher than a regular incoherent imaging system with the same NA, but the unwanted direct current (dc) term and twin image are superimposed on the reconstructed image. Phase-shifting technology[21,22] is widely used to extract dc term and twin image. Traditional three-step phase-shifting technology must record at least three holograms in sequence, which is not suitable for instantaneous measurements. The image reconstructed by the two-step phase-shifting cannot eliminate the unwanted items, so its quality is relatively poor.

To both exceed recording many times and achieve a phase-shifted method for instantaneous measurement, Wan[23] combined FINCH with parallel phase-shifting technique to obtain a spatially multiplexed hologram of four-step phase-shifting FINCH instantaneously. The hologram is demultiplexed into four undersampled phase-shifted holograms with a sampling rate of only 25%. The more the multiplexing, the narrower the spatial bandwidth of each hologram will be, and the reconstruction quality will decrease. To realize the parallel two-step phase-shifting FINCH for real time imaging, it is extremely urgent and important to do research on two-step phase-shifting algorithm. In Ref. [24], the complex amplitude of an object is calculated by using the intensity of reference wave and two holograms, but the FINCH system is a single-path configuration, neither object wave nor reference wave can be separated. In 2009, Meng *et al.*[25] and Liu and Poon[26] proposed a two-step phase-shifting algorithm to remove the dc term and twin image. Though this algorithm was optimized in 2011, it was still complex and computationally intensive. In Ref. [27], Hanning filter was utilized to retrieve the low frequency bias from a hologram, then the dc term can be subtracted from the recorded holograms.

In this work, we present a method of enhancing the resolution, the method that is two-step phase-shifting Fresnel incoherent correlation holography based on discrete wavelet transform. After two-step phase-shifting technology, using this approach can separate high frequency and low frequency infor-

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mation in a hologram layer by layer, so it is more effective to segregate dc term from the measurement information for enhancing resolution. This method is verified by comparing with different image processing results on the same experimental object and by obtaining the same result on different objects. In addition, the method improves the spatial utilization in a parallel phase-shifting holography system while ensuring the quality of reconstruction.

2. Theory

In this section, the experimental setup and the theory of discrete wavelet transform are introduced.

2.1. Experimental setup

In the experimental setup, incoherent light wave emitted from the white light source (CEL-TCX250, 250 W) is collimated by a lens L_1 with a 60-mm focal length, and then it passes through a narrow (20 nm) bandwidth filter with a central wavelength of 632.8 nm. The wave is split into two beams by a spatial light modulator (SLM, Holoeye Pluto 1920 $\times$1080 pixels, 8-μm pixel pitch, phase only modulation), the FINCH system produces self-interference for each object point and incoherently superimposes them to create a Fresnel hologram. The hologram is captured by a CCD camera (QImaging Retiga 6000, 2750$\times$2200 pixels, 4.54-μm pixel pitch) and finally stored in an image processing system. The distance between L_2 and SLM is 140 mm, and the sum of the distance from BS_2 to SLM and the distance from BS_2 to CCD is 250 mm.

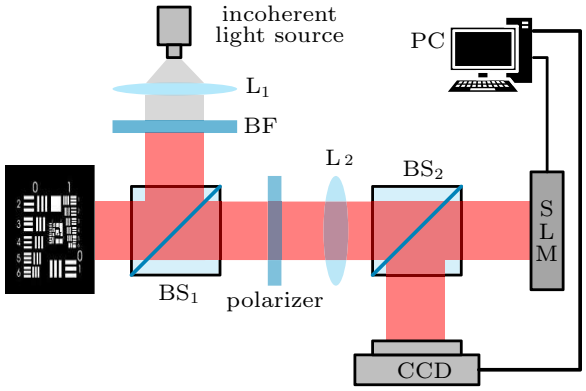


Fig. 1. Optical setup of Fresnel incoherent correlation holography.

2.2. Wavelet decomposition and reconstruction

In two-step phase-shifting technology, an object point was located at the point (x_s, y_s, z_s). We mounted dual-lens patterns on an SLM. Two holograms ($\boldsymbol{H}_1$ and $\boldsymbol{H}_2$) with different phase shifts can be obtained by CCD, and the two phase shifts have the relationship $\theta_2 = \pi/2 + \theta_1$, and angle θ_1 is at an arbitrary value. In our work, we chose $\theta_1 = 0$ and $\theta_2 = \pi/2$. The resulting hologram $\boldsymbol{H}_R(x,y)$ is a superposition according to the following equation:

$$\begin{aligned}\boldsymbol{H}_R(x,y) = \frac{1}{2}\left(\boldsymbol{H}_1(x,y) + \mathrm{i}\boldsymbol{H}_2(x,y)\right) = C' \iiint g(x_s,y_s,z_s)\,\mathrm{d}x_s\,\mathrm{d}y_s\,\mathrm{d}z_s \\ + C_1 \iiint g(x_s,y_s,z_s)\exp\left\{-\frac{\mathrm{i}\pi}{\lambda Z_r}\left[(x - M_T x_s)^2 + (y - M_T y_s)^2\right]\right\}\mathrm{d}x_s\,\mathrm{d}y_s\,\mathrm{d}z_s, \end{aligned} \tag{1}$$

where C' and C_1 are constant, $\boldsymbol{H}_R(x,y)$ represents the information about a hologram containing three terms, which are dc term, the linear phase, and real image. According to Eq. (1), the dc term is superposed on a resulting hologram, so the resolution of reconstructed image is lower. In order to improve the quality of image, it is significant to get rid of the dc term.

Wavelet analysis has been widely used in image processing, medical imaging and diagnosis.[28–32] Discrete wavelet transform (DWT) can be regarded as being equivalent to filtering the input signal with a bank of band-pass filters. The low-frequency represents a summary and high-frequency represents fine details of a signal, both are essential in signal analysis and representation.

Figure 2 shows the diagram of decomposition. At each round of DWT, low-resolution signal (low frequency D) and fine details signal (high frequency P) are obtained, this actual process is called decomposition level process. At the first step of decomposition, due to the separability property of DWT, two passes at each round of the DWT are done at rows and columns separately. One level DWT is used to decompose an input image into different sub-band images as shown in Fig. 2(a), and the result of this step is to produce four sub-regions, which are summary (DD), vertical details (DP), horizontal details (PD), and diagonal details (PP).[33] The above steps are repeated on the DD image for the next round of DWT as shown in Fig. 2(b).

The wavelet coefficients of each level after decomposition can be expressed as follows:

$$\begin{cases} T_{n+1}(x,y) = T_n L(x) L(y), \\ K^h_{n+1}(x,y) = T_n L(x) G(y), \\ K^v_{n+1}(x,y) = T_n G(x) L(y), \\ K^d_{n+1}(x,y) = T_n G(x) G(y), \end{cases} \quad n = 0,1,\ldots,n-1, \tag{2}$$

where T_{n+1} is a set of low-frequency sub-classes; K_{n+1} is a set of high-frequency sub-classes; G and L correspond to the high pass filter and low pass filter, respectively; superscripts (h, v, d) correspond to the horizontal direction, vertical di-

rection and diagonal direction; n denotes the decomposition level.[34,35] As the level of decomposition increases, the more information will be filtered out, choosing the most appropriate value for the least loss.

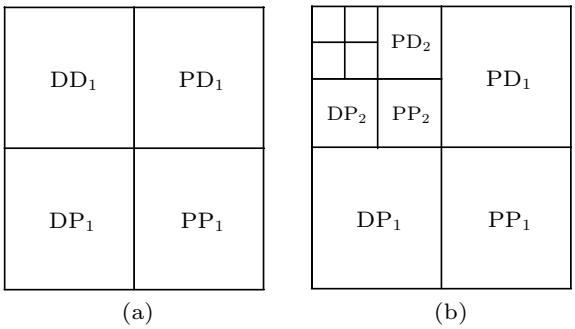


Fig. 2. 2D-DWT decomposition at (a) level 1 and (b) level 3.

Resulting hologram $\boldsymbol{H}_{\mathrm{R}}(x,y)$ is calculated with two phase-shifted holograms according to Eq. (1), then the resulting hologram is decomposed by using the DWT. The wavelet decomposition divides the data of the hologram into approximate parts (low-frequency) and detailed parts (high-frequency), and the approximate parts with the highest level of decomposition are extracted. The other parts reconstruct a new hologram $\boldsymbol{H}'_{\mathrm{R}}(x,y)$. In the digital holography, the diffraction process is simulated on a computer and digitally reproduced, then an image $S(x,y,z)$ can be reconstructed from $\boldsymbol{H}'_{\mathrm{R}}(x,y)$ by ASM as follows:

$$S(x,y,z) = F^{-1}\left\{F[\boldsymbol{H}'_{\mathrm{R}}(x,y)]\exp\left[\mathrm{i}kz_{\mathrm{r}}\sqrt{1-\lambda^2\left(f_x^2+f_y^2\right)}\right]\right\}, \quad (3)$$

where $k=2\pi/\lambda$, F and F^{-1} represent the forward and inverse Fourier transform, respectively, f_x and f_y are the frequency domain coordinates corresponding to x and y.

3. Results and discussion

In this paper, we propose that the DWT can be used to eliminate the dc term of a hologram after two-step phase-shifting technology. Qin *et al.*[28] utilized a Hanning filter to retrieve the low frequency in hologram, and this method indicates that with a hologram multiplied by a filter function, a single filter can be achieved. While in our proposed method the DWT is used to decompose a hologram from four directions into different layers, and repeating this process for retrieving the low frequency information layer by layer, we can obtain a clearer reconstructed image finally.

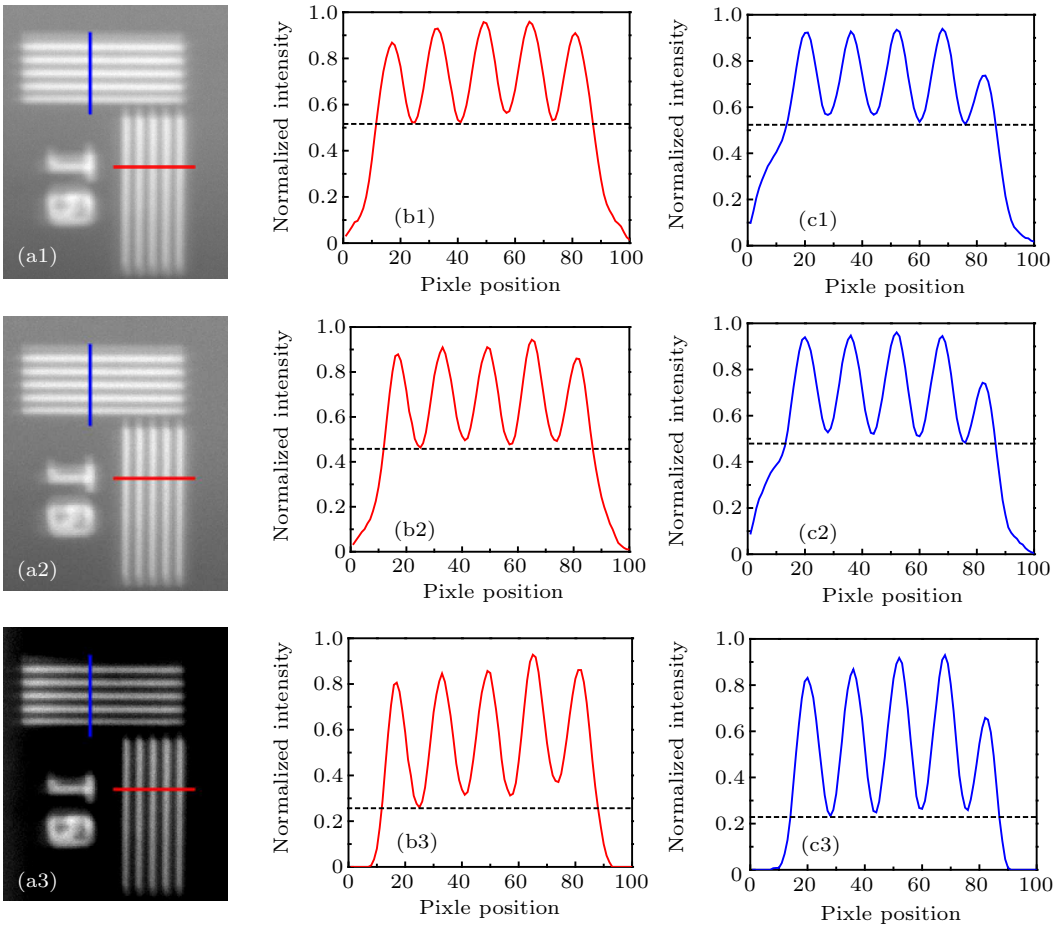


Fig. 3. Reconstructed images obtained by (a1) traditional two-step phase-shifting technology, (a2) Hanning filter, (a3) proposed method, [(c1)–(c3)] intensity distributions at positions of red line and blue line in panels (a1)–(a3), respectively.

Figure 3 shows the reconstructed images with different methods. We use program to obtain intensity–pixel graphs by drawing lines at the same position in each reconstructed image, and the existence of line pairs is represented by the change of intensity values in the graph. The dotted line indicates the intensity of background noise and the height between peak value and dotted line represents the resolution. Figures 3(b1)–3(b3) and 3(c1)–3(c3) show the intensity distributions of red line and blue line of Figs. 3(a1)–3(a3), respectively. Figure 3(a2) illustrates that Hanning filter can reduce the dc term, but the dc term cannot be completed removed . The reconstructed image obtained by our proposed technique is shown in Fig. 3(a3), and we can see that the noise value is reduced, the peak value does not change, and resolution is enhanced. The minimum value of intensity distribution corresponding to the red line in Fig. 3(b3) is much smaller than in Fig. 3(b2), which means that the background noise is extracted completely, and the resolution is much higher. We can obtain an identical result from the blue line. Experimental results show that this method can extract the dc term from horizontal and vertical direction, and improve the quality of reconstructed image. It is fully confirmed that this proposed method achieves higher-resolution imaging with the two-step phase-shifting technology by extracting the approximate parts.

In order to be able to quantify the effect of the proposed method on resolution, we consider a high-resolution 1951 USAF test target as an object. Three reconstructions are shown in Fig. 4. Using the traditional two-step phase-shifting technology, the resolved elements in the reconstructed image Fig. 4(a1) are G3–E3 (point *A*) corresponding to a cutoff frequency of 10.08 lp/mm. Figure 4(a2) shows the reconstructed image with Hanning filter, and we can see that the element 2 (point *B*) in group 4 is clear, but the images of group 4 above element 3 are blurry, so its frequency is 17.96 lp/mm. From Fig. 4(b3), the element 3 (point *C*) in group 4 can be distinguished, the limit in the spatial resolution can be extended up to 20.16 lp/mm by using the proposed method. The conclusion from these observations is that the resolution of the hologram reconstruction is enhanced by our proposed method.

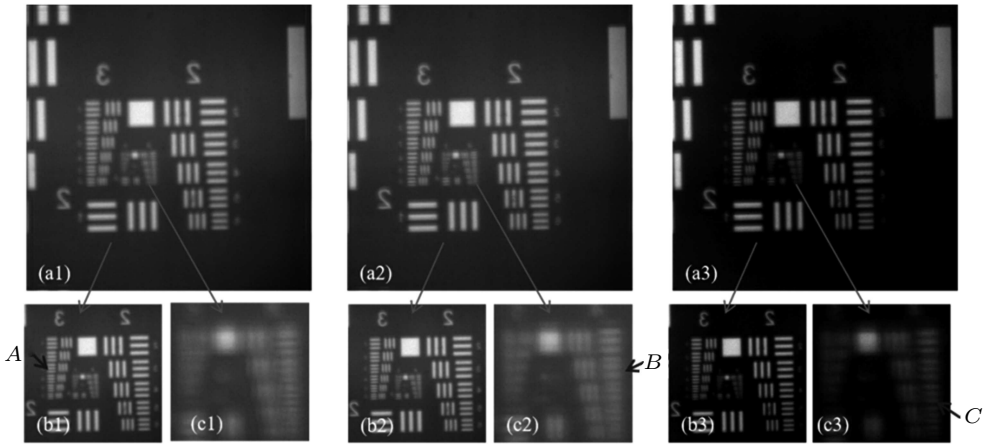


Fig. 4. Reconstruction images, obtained by (a1) traditional two-step phase-shifting technology, (a2) Hanning filter, (a3) proposed method, with panels (b1)–(b3) corresponding to groups 2 and 3 of panels (a1)–(a3), respectively, and panels (c1)–(c3) corresponding to groups 4 and 5 of panels (a1)–(a3), respectively.

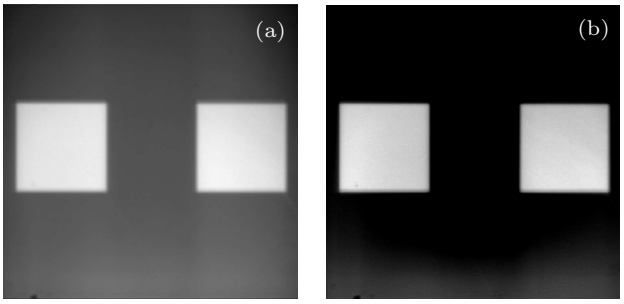


Fig. 5. Reconstructed images obtained by (a) traditional two-step phase-shifting technology and (b) proposed method.

In order to demonstrate the influence of our proposal, we use blocks with obvious gray values in the experiments: each block is 1.5 mm×1.5 mm in size. The reconstructed images with different methods are shown in Fig. 5. It can be seen from the experimental results that the background of traditional method is obviously brighter, but the edges of block are blurred. It indicates that the background noise of reconstructed image obtained with traditional two-step phase-shifting technology is larger than with the DWT under the same holographic recording conditions. Hence, the DWT is an effective tool to extract the dc term, thereby being able to improve the quality of reconstructed image.

Figure 6 shows the experimental results for a 'cat'. Two holograms with different shifts are continuously recorded by CCD, which are shown in Figs. 6(a) and 6(b). We use different methods to implement the image reconstruction of two identical holograms. The comparison of Fig. 6(c) with Fig. 6(d) shows that the presence of the dc term blurs the reconstructed image and makes the edge of the test subject inaccurate. The reconstructed image obtained by the proposed method is much

clearer than by the traditional two-step phase-shifting technology. Thus, the proposal can extract the dc term within a high accuracy, and is effective to image real objects. In addition, compared with the three-step phase-shifting technology, two-step phase-shifting technology only needs recording twice, which reduces the number of shots. It can also reduce multiplexing and increase space utilization in a parallel phase-shifting technology system.

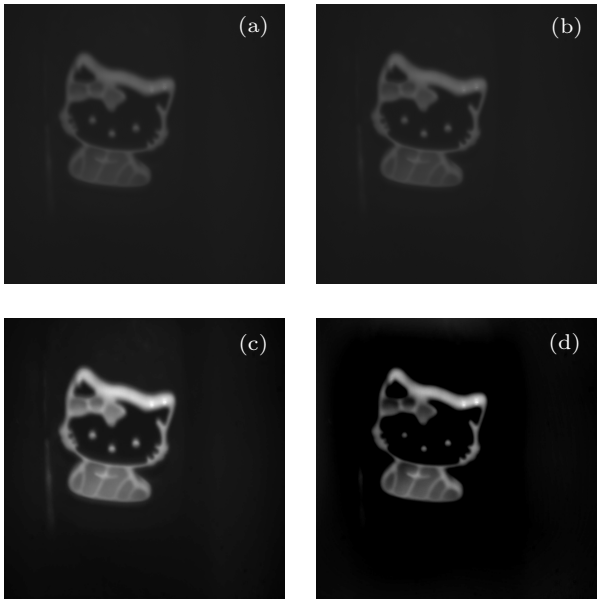


Fig. 6. Experimental result, showing (a) 0° phase shift hologram, (b) 90° phase shift hologram, (c) reconstructed image obtained with traditional two-step phase-shifting technology, and (d) reconstructed image obtained with proposed method.

4. Conclusions

In this paper, an effective method based on the two-step phase-shifting technology is proposed to improve the quality of reconstructed image. We capture two holograms with CCD, and use the two-step phase-shifting technology to obtain a resulting hologram, the resulting hologram is a superposition of multiple forms. Decomposing the resulting hologram into different sub-bands according to the theory of DWT, and reconstructing image after filtering out the dc term, it is sensible to retain a higher resolution in a very low-frequency band, because low-frequency information is much more important than high-frequency information to human perception. On this basis, experimental reconstructions of some objects are used to verify the effectiveness of this method. The DWT can suppress the influence from the dc term more efficiently, thereby improving the quality of reconstructed image. And the two-step phase-shifting technology only involves the acquisition of holograms with two phase shifts, so this method can reduce spatial multiplexing and improve device applications in a parallel phase-shifting system while ensuring image quality.

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