A novel method to obtain electronic speckle pattern interferometry fringe patterns with high contrast

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Traditional speckle fringe patterns of electronic speckle pattern interferometry (ESPI) are obtained by adding, subtracting, or multiplying the speckle patterns recorded before and after the deformation. However, these speckle fringe patterns are of limited visibility, especially for addition and multiplication fringe patterns. We propose a novel method to obtain speckle fringe patterns of ESPI from undeformed and deformed speckle patterns. The fringe pattern generated by our method is of high contrast and has better quality than subtraction fringe. The new method is simple and does not require more computational effort. The proposed method is tested on the experimentally obtained undeformed and deformed speckle patterns. The experimental results illustrate the performance of this approach.

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Electronic speckle pattern interferometry (ESPI) is a well-known non-destructive whole-field technique for measuring displacements and is widely applied in various fields[1]. Accurate extraction of phase value is of fundamental importance for the successful application of ESPI[2,3]. The phase-shifting technique is one of the most commonly used methods. However, commonly used phase shifting methods require at least three speckle fringe patterns with certain phase differences. Even the single-phase-step methods also require undeformed, deformed, and introduced $\pi/2$ phase-shift speckle patterns[4]. In the measurement of objects in fast motion or in a temporally unstable environment, it is difficult to take several phase-shifted interferograms in an extremely short period[5]. Therefore, the need for processing a single fringe pattern arises. There are many techniques to estimate the phase term from a single fringe pattern, such as the Fourier transform method[6], the phase-locked loop method[7], and regularized phase tracker[8]. No matter which type of technique is used for extraction of phase from a single fringe pattern, it is very important that ESPI fringe patterns are of good visibility[9]. Traditional ESPI fringe patterns obtained by two undeformed and deformed speckle patterns are of limited visibility, so special techniques are needed to remove the noise and enhance the contrast of ESPI fringe patterns[10]. In addition, the direct correlation method can generate the fringe patterns by performing a direct correlation between two original speckle patterns[11]. The main disadvantage of the method is that the calculations to carry out the correlation require more computational effort than that needed for the frame subtraction method.

In this letter, we present a novel method to obtain the fringe patterns of ESPI from the two original speckle patterns. The ESPI fringe pattern obtained by our method is of high contrast and has better quality even than subtraction fringe patterns. The new method is simple and can solve the problem encountered by the direct correlation. We test the proposed method on the experimentally obtained speckle patterns. The results are encouraging and demonstrate the performance of the new method.

ESPI depends on intensity maps recorded before and after the surface of a specimen is deformed. Under unstressed conditions, the intensity $I_1(x,y)$ at any point (x,y) is

$$I_1 = I_\mathrm{o} + I_\mathrm{r} + 2\sqrt{I_\mathrm{o}I_\mathrm{r}}\,\cos\,(\phi_\mathrm{r} - \phi_\mathrm{o}), \tag{1}$$

where I_o and I_r are the intensities of the object and the reference beams, respectively; ϕ_o and ϕ_r are the phases of the undeformed object light beam and the reference light beam, respectively; and $(\phi_\mathrm{o} - \phi_\mathrm{r})$ is the random interferometric phase of the speckle field. After deformation, the intensity at any point (x,y) becomes

$$I_2 = I_\mathrm{o} + I_\mathrm{r} + 2\sqrt{I_\mathrm{o}I_\mathrm{r}}\,\cos\,(\phi_\mathrm{r} - \phi_\mathrm{o} + \delta), \tag{2}$$

where δ is the phase change due to the deformation of surface of the tested object. The variable dependence on (x,y) is dropped for brevity, however, it is implied in all variables.

We rearrange Eqs. (1) and (2) as

$$I_1(x,y) = A(x,y)\left[1 + \gamma(x,y)\cos\,\phi(x,y)\right], \tag{3}$$

$$I_2(x,y) = A(x,y)\left\{1 + \gamma(x,y)\cos\left[\phi(x,y) + \delta(x,y)\right]\right\}, \tag{4}$$

where $A(x,y) = I_\mathrm{o} + I_\mathrm{r}$, $\gamma(x,y) = \frac{2\sqrt{I_\mathrm{o}I_\mathrm{r}}}{I_\mathrm{o}+I_\mathrm{r}}$, $\phi(x,y) = \phi_\mathrm{r} - \phi_\mathrm{o}$. $A(x,y)$ is a slowly varying background illumination, $\gamma(x,y)$ is related to the amplitude modulation. Here we may assume that A and γ are constant over the region of interest. This requirement on A and γ is equivalent to requiring that different pixels in the region of interest are the same except for the effect of the phase term $\delta(x, y)$. Under this condition, Eqs. (3) and (4) can be expressed as

$$I_1(x,y) = A\left[1+\gamma\cos\phi(x,y)\right], \qquad (5)$$

$$I_2(x,y) = A\left\{1+\gamma\cos\left[\phi(x,y)+\delta(x,y)\right]\right\}, \qquad (6)$$

Further, Eqs. (5) and (6) are rearranged as

$$\cos[\phi(x,y)] = h(x,y), \qquad (7)$$

$$\cos\left[\phi(x,y)+\delta(x,y)\right] = g(x,y), \qquad (8)$$

where $h(x,y) = \frac{I_1(x,y)-A}{\gamma}$, $g(x,y) = \frac{I_2(x,y)-A}{\gamma}$, which are the normalized intensities.

Now, let us focus on solving the phase at every pixel by using Eqs. (7) and (8). For solving the phase $\delta(x,y)$, it is reasonable that we assume the phase $\delta(x,y)$ is a constant over the small window of (3×3), and limit the phase δ and term ϕ for this algorithm within $0-2\pi$. These assumptions are also used in the other phase-shift calibration algorithms (see Ref. [12]). Let the subscript denote the coordinates of pixel, for example, $\delta_{i,j}$ denoting the phase of pixel (i,j). The whole image size is $m\times n$.

According to Eq. (7), we calculate the term ϕ at pixel(i,j). $\phi\in[0,\ 2\pi]$, so we can obtain two ϕ values at pixel (i,j) denoted by $\phi^1_{i,j}$, $\phi^2_{i,j}$, respectively:

$$\phi^1_{i,j} = \arccos(h_{i,j}), \quad \phi^2_{i,j} = 2\pi - \arccos(h_{i,j}). \qquad (9)$$

Similarly, according to Eq. (8), we calculate the phase δ at pixel (i,j). $\phi\in[0,\ 2\pi]$ and $\delta\in[0,\ 2\pi]$, so $(\phi+\delta)\in[0,\ 4\pi]$, and we obtain four $(\phi+\delta)$ values at pixel (i,j) denoted by $(\phi+\delta)^1_{i,j}$, $(\phi+\delta)^2_{i,j}$, $(\phi+\delta)^3_{i,j}$, and $(\phi+\delta)^4_{i,j}$:

$$\begin{aligned}&(\phi+\delta)^1_{i,j} = \arccos(g_{i,j}), (\phi+\delta)^2_{i,j} = 2\pi - \arccos(g_{i,j}),\\&(\phi+\delta)^3_{i,j} = 2\pi + \arccos(g_{i,j}),\\&(\phi+\delta)^4_{i,j} = 4\pi - \arccos(g_{i,j}).\end{aligned} \qquad (10)$$

Then, we obtain eight possible phase values at pixel (i,j) denoted by $\delta^k_{i,j}(k=1,\cdots,8)$:

$$\begin{aligned}&\delta^1_{i,j} = (\phi+\delta)^1_{i,j} - \phi^1_{i,j}, \quad \delta^2_{i,j} = (\phi+\delta)^1_{i,j} - \phi^2_{i,j},\\&\delta^3_{i,j} = (\phi+\delta)^2_{i,j} - \phi^1_{i,j}, \quad \delta^4_{i,j} = (\phi+\delta)^2_{i,j} - \phi^2_{i,j}\\&\delta^5_{i,j} = (\phi+\delta)^3_{i,j} - \phi^1_{i,j}, \quad \delta^6_{i,j} = (\phi+\delta)^3_{i,j} - \phi^2_{i,j},\\&\delta^7_{i,j} = (\phi+\delta)^4_{i,j} - \phi^1_{i,j}, \quad \delta^8_{i,j} = (\phi+\delta)^4_{i,j} - \phi^2_{i,j},\end{aligned} \qquad (11)$$

where $1\le i\le m$, $1\le j\le n$. Thus, we obtain eight possible phase values at every pixel in the whole image. Consequently, we report in detail on how we find the most reasonable phase from eight possible phase values at every pixel.

Given the current pixel (i,j), it has eight neighbors in a small window of (3×3) whose coordinates are given by $(i+l_1, j+l_2)$, $-1\le l_1\le 1$, $-1\le l_2\le 1$, both l_1 and l_2 are integers, and not equal to zero at the same time. We will choose the optimal one of eight possible $\delta^k_{i,j}$ $(k=1,\cdots,8)$ by its neighbors. The procedure of choice is shown as follows.

Firstly, fixing $\delta^k_{i,j}$ $(k=1,\cdots,8)$ in turn. As mentioned above, we have obtained two possible ϕ values at every pixel. Now we choose a more reasonable $\phi^k_{i+l_1,j+l_2}$ at each neighboring pixel $(i+l_1, j+l_2)$ of the current pixel (i,j) from $\phi^1_{i+l_1,j+l_2}$ and $\phi^2_{i+l_1,j+l_2}$.

According to the above-mentioned assumption, we have

$$\delta^k_{i+l_1,j+l_2} \approx \delta^k_{i,j}.$$

We calculate $\cos(\phi^1_{i+l_1,j+l_2} + \delta^k_{i+l_1,j+l_2})$ and $\cos(\phi^2_{i+l_1,j+l_2} + \delta^k_{i+l_1,j+l_2})$ denoted by $s^{k,1}_{i+l_1,j+l_2}$, $s^{k,2}_{i+l_1,j+l_2}$, respectively, and compare the calculated values with $g_{i+l_1,j+l_2}$ obtained by Eq. (8). Corresponding to $\delta^k_{i,j}$, the chosen $\phi^k_{i+l_1,j+l_2}$ at each neighboring pixel $(i+l_1, j+l_2)$ is

$$\phi^k_{i+l_1,j+l_2} = \begin{cases}\phi^1_{i+l_1,j+l_2}, \text{if}\left(\left|s^{k,1}_{i+l_1,j+l_2} - g_{i+l_1,j+l_2}\right| < \left|s^{k,2}_{i+l_1,j+l_2} - g_{i+l_1,j+l_2}\right|\right)\\ \phi^2_{i+l_1,j+l_2}, \text{if}\left(\left|s^{k,1}_{i+l_1,j+l_2} - g_{i+l_1,j+l_2}\right| > \left|s^{k,2}_{i+l_1,j+l_2} - g_{i+l_1,j+l_2}\right|\right)\end{cases}. \qquad (12)$$

The calculated value $\cos(\phi^k_{i+l_1,j+l_2}+\delta^k_{i+l_1,j+l_2})$ is denoted by $s^k_{i+l_1,j+l_2}$.

Secondly, we define $Er^k_{i,j}$ as the sum of the square of the difference between $s^k_{i+l_1,j+l_2}$ and $g_{i+l_1,j+l_2}$:

$$Er^k_{i,j} = \sum_{l_1=-1}^{1}\sum_{l_2=-1}^{1}(s^k_{i+l_1,j+l_2} - g_{i+l_1,j+l_2})^2. \qquad (13)$$

Eight values $Er^k_{i,j}$ $(k=1,\cdots,8)$ at the current pixel (i,j) can be obtained. Then the minimum of $Er^k_{i,j}$ is found, and the corresponding phase is regarded as the most reasonable phase of the current pixel (i,j).

Under the assumption the undeformed and deformed speckle patterns have been recorded, the steps to implement the proposed method for extracting the full phase field of ESPI are summarized as follows.

Step 1: Calculating the normalized intensities $h_{i,j}$ and $g_{i,j}$ at every pixel.

Step 2: Calculating the terms $\phi^1_{i,j}$, $\phi^2_{i,j}$ at every pixel based on Eq. (9); calculating $(\phi+\delta)^1_{i,j}$, $(\phi+\delta)^2_{i,j}$, $(\phi+\delta)^3_{i,j}$, and $(\phi+\delta)^4_{i,j}$ at every pixel based on Eq. (10).

Step 3: Obtaining eight possible phase values $\delta^k_{i,j}$ $(k=1,\cdots,8)$ at pixel (i,j) by Eq. (11).

Step 4: Finding the most reasonable phase from eight possible phase values $\delta^k_{i,j}$ $(k=1,\cdots,8)$ at every pixel.

For evaluating the real performance of the proposed method, we test the method on the experimentally obtained patterns, and compare the results with traditional subtraction fringe pattern. Figures 1(a) and (b) give the experimentally obtained undeformed and deformed speckle pattern pair with image size of 523× 523 pixels, which depict the out-of-plane displace-ment of a circular plate. The plate is rigidly clamped at its boundary and is subject to a central load. Figure 1(c) gives the fringe pattern obtained by our new method using the undeformed and deformed speckle pattern pair.

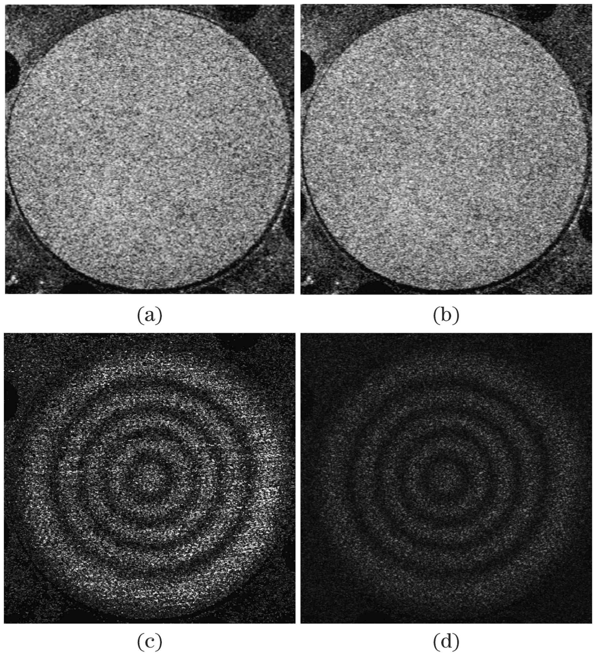

Fig. 1. Experimentally obtained undeformed and deformed speckle pattern pair and its fringe patterns. (a) Speckle pattern before deformation; (b) speckle pattern after deformation; (c) the fringe pattern obtained by our method; (d) subtraction fringe pattern.

The subtraction fringe pattern obtained by Eqs. (1) and (2) with the same speckle pattern pair is shown in Fig. 1(d). The computation time for Fig. 1(c) is 19.9 s.

As we can see, the contrast and visibility in the subtraction fringe pattern are low. From the undeformed and deformed speckle patterns, it is apparent that the illumination is not uniform, but the generated ESPI fringe pattern by the new method is of high contrast and has better visual inspection than the traditional subtraction fringe pattern. One can find that the proposed method gives the superior result.

In conclusion, we have presented and tested an alternative method to obtain fringe pattern from two speckle patterns before and after deformation. The method is novel and completely different from the other phase-shift calibration algorithms. The ESPI fringe pattern generated by the new method is of good contrast and visibility. In addition, the new method is simple, and its calculation cost has been reduced as compared with the direct correlation and the other phase-shift calibration algorithms. The proposed method enlarges the techniques and applications of ESPI, especially for the harsh environmental tests that fringe patterns have poor visibility. We have demonstrated the performance of the new method via applications in the experimental speckle patterns.

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