Phase-tilting interferometry for optical testing

Jianxin Li,* Rihong Zhu, Lei Chen, and Yong He

School of Electronic Engineering and Optoelectronic Technology, Nanjing University of Science and Technology, Nanjing 210094, China
*Corresponding author: ljx@vip.163.com

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Phase-tilting interferometry for optical testing is proposed to retrieve the phase from interferograms with random phase tilts. The Radon transform is used to extract the tilted phase plane, and the phase distribution is retrieved by the least squares method. The proposed method has been applied to simulated and experimental interferograms, obtaining satisfactory results. The proposed method has high accuracy and good robustness, and it can be used for interferometric measurements in environmental vibrations. Additionally, it can be used for interferometers without a phase shifter to achieve high-precision analysis. © 2013 Optical Society of America

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Phase-shifting interferometry (PSI) has been widely used in recent decades for optical testing through digital fringe analysis to retrieve phase distribution. In standard PSI, a sequence of interferograms is acquired using the phase shifter to produce a constant phase shift of \(2\pi/N\) between adjacent interferograms, where the integer \(N \geq 3\). Some N-step phase-shifting methods have been proposed to achieve efficient resistance to phase-shift errors [1]. These methods are widely used in a variety of phase-measurement applications.

In standard PSI, phase calibration is necessary to obtain equal phase shifts. Unfortunately, the calibration is not easy since it depends on the complicated hardware of the phase shifter. Also, its stability will become unreliable during long-time use. Several random phase-shifting methods without any prior knowledge about the phase shifts are proposed [2–4]. However, with environmental vibrations, neither standard PSI nor random PSI can suppress the errors caused by inaccurate phase shift. Vibration produces unknown changes to the phase shifts and tilts, so the retrieved phase falsely interprets as a surface variation. Much effort has been marshaled against vibrations, such as instantaneous interferometry [5,6], vibration-compensated method [7,8], tilt-compensated method [9], carrier squeezing interferometry [10], and others with various complicated strategies [11,12].

In this Letter, we propose a new phase-tilting interferometry (PTI) to retrieve the phase from interferograms with random phase tilts. Our method does not need perfect equal phase shifts or consistent tilts.

The intensity distribution of an interferogram can be described using the following expression:

\[
I(x, y) = a(x, y) + b(x, y) \cos(\phi(x, y)),
\]

where \(a(x, y)\) is the background intensity and \(b(x, y)\) and \(\phi(x, y)\) are the modulation amplitude and phase map, respectively.

If the interferograms are acquired under different tilt directions and angles, the sequence of interferograms can be rewritten as

\[
I_n(x, y) = a(x, y) + b(x, y) \cos(\phi(x, y) + P_n(x, y)).
\]

where \(n = 1, 2, \cdots, N\). \(P_n(x, y)\) is the tilted phase plane and it can be defined as

\[
P_n(x, y) = \alpha_n x + \beta_n y + \gamma_n.
\]

From Eqs. (1) and (2), we obtain the difference of two interferograms:

\[
D_n(x, y) = I_n(x, y) - I(x, y) = -2b(x, y) \sin((\phi(x, y) + P_n(x, y))/2) \sin(P_n(x, y)/2).
\]

When \(D_n(x, y) = 0\), there exists \(\sin(P_n(x, y)/2) = 0\) or \(\sin((\phi(x, y) + P_n(x, y))/2) = 0\). We obtain a binary image \(D_n'(x, y)\) according to the following criterion:

\[
D_n'(x, y) = \begin{cases} 
1, & D_n(x, y) = 0 \\
0, & \text{others}
\end{cases}
\]

If the carrier frequencies of the two interferograms differ greatly, a group of parallel straight lines will appear in the image \(D_n'(x, y)\) corresponding to \(\sin(P_n(x, y)/2) = 0\), shown as the white lines in Fig. 1(a). The black curves shown in the figure correspond to \(\sin((\phi(x, y) + P_n(x, y))/2) = 0\). The tilted phase plane can be determined by the line detection algorithm of the parallel straight lines. There are many methods of line detection; for example, Hough transform [13] and Radon transform.

Fig. 1. Radon transform of binary image. (a) Binary image of the difference between two interferograms. (b) Image obtained by Radon transform.
frequency of fringe patterns for PSI. While using PTI, the phase can effectively suppress the vibration errors. Finally, the analysis of PV and rms is performed. The PV and rms of PTI are \(0.2081\lambda\) and \(0.0402\lambda\), and those of PSI are \(0.2332\lambda\) and \(0.0416\lambda\), respectively. From the results of the experiment, we can see that our proposed method has good performance.

The experiments above show the effectiveness of PTI, but the following factors should be considered. First, a substantial carrier frequency should be introduced in the reference interferogram. The accurate calculation of the interval between adjacent peaks requires relatively high carrier frequency of the reference interferogram. According to the experimental analysis, more than 10 interference fringes can almost meet the requirements. In order to avoid the so-called retrace error, often the low carrier frequency is suitable for PSI. However, with PTI, the high carrier frequency of the reference interferogram does not lead to system errors because the calculation of the wrapped phase does not need the reference interferogram. In the case of measuring objects with higher form deviation, local subsampled fringes will appear while the object is tilted. The maximum tolerable local surface tilt of the interferograms \(I_{\phi}(x,y)\) is limited, and it should be controlled to avoid local subsampled fringes.

Second, the number of tilted interferograms will have an impact on stability. As for the intensities in the same position of the interferograms, the phase shifts caused by tilting may be very small or even close to zero. Instability may occur without enough interferograms in the process of calculating the phase. More interferograms can guarantee a more reasonable distribution of phase shifts and higher precision of the calculation. However, the acquisition of too many interferograms will lead to high computational requirements. On the basis of the experimental analysis, 10 interferograms or more will ensure the stability of the results.

Third, the interval between the adjacent peaks should be resolved in fractional coordinates. In the calculation of the tilted plane coefficients, the angle \(\theta\) and the distance \(\rho\) are obtained robustly and accurately because it is very easy to find the maximum peak. In contrast, it is more complicated to find the interval \(d\). In the \(\rho-\theta\) transform domain, the peaks are located in the integer coordinates, while the interval \(d\) is usually not an integer value. Therefore, we need to calculate the average interval of all adjacent peaks. The methods of finding extreme in an image area can be used in detecting the peaks, and the robustness of the process can be improved by means of noise smoothing.

In summary, we present a PTI to retrieve the phase from interferograms with random phase tilts. The proposed method allows low carrier frequency of the interferograms to avoid system errors caused by the lack of a common path. The method has high accuracy and good robustness and can be used for interferometric measurements when severe vibrations are presented. Especially for large-aperture interferometers with a large and complicated optical system, it is always very sensitive to environmental vibrations during the phase shifting. The method can accurately extract the tilted plane of each interferogram and effectively suppress the vibration errors. Additionally, by using the method, the expensive phase-shifting devices in the interferometer are no longer required for high-precision analysis.

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