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Fast spatial carrier phase-shifting algorithm based on a constructed reference-phase

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ABSTRACT

A fast and straightforward spatial carrier phase-shifting (SPS) algorithm based on a constructed reference phase is presented. This reference phase is obtained from the interferogram carrier-frequency values, and the interesting phase can be directly extracted from a single interferogram without any carrier-removal operation. Numerical simulations show that the computation times when it is used the proposed method are approximately 4.5 times faster than the Fourier transform approach and about 2 orders of magnitude faster than the least-square SPS method. The proposed method can be applied to phase measurements for high-speed dynamic or moving objects.

1. Introduction

Unlike phase-shifting (PS) methods, the main advantage of the spatial carrier approaches is that they allow phase measurements by a single pattern in a single-shot measurement [1]. Therefore, they are insensitive to vibration and environment turbulence and allow the measurement of dynamic processes or moving object fields. The Fourier transform method (FTM) [2–8] and the spatial carrier phase-shifting (SPS) approach [9–13] are the two most popular spatial carrier methods. However, there are still some unsolved problems such as carrier-removal error, spectral leakage and boundary effect because of Gibbs effects in the FTM [5,7,8]. Recently, another two time-frequency analysis methods as the windowed Fourier transform (WFT) [14–16] and wavelet transform (WF) [17,18], have been introduced. These approaches can solve the problems mentioned above to a somehow extent.

The SPS method attempts to combine the advantages of the FTM and temporal phase-shifting (PS) approaches. The SPS approach composes a set of phase-shifted fringe patterns from the original carrier interferogram, then the modulating phase is obtained from phase-shifting demodulating techniques but using the spatial dimension instead of the temporal one [9,10]. While the SPS methods need prior knowledge about the carrier-frequency or phase-shifting values. Guo et al. [19] presented a two-step method that first estimates the local frequency, and then calculates the phase distribution by a least-squares method. However, the results are unstable due to the variations in the fringe pattern background and contrast signals [20]. Additionally, Xu et al. [21] presented an excellent SPS algorithm, which obtains high retrieval precision and advanced stability by an iterative least-squares approach (named LSI-SPS). The main drawback of this approach is that it requires high processing time [22,23]. Recently, a non-iterative spatial phase-shifting algorithm based on principal component analysis is proposed in our group [24]. It is a fast and effectively PS algorithm and it can be used to directly extract the phase from only a single spatial carrier interferogram based on the principal component analysis method [25–27].

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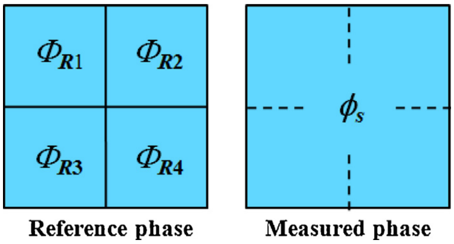

Fig. 1. Reference phase and the measured phase distributions at the four neighboring pixels on the carrier interferogram.

In this paper, we present a fast and straightforward SPS algorithm based on a constructed reference phase to directly extract the interesting phase from a single carrier interferogram. If the carrier-frequency values of the fringe pattern are known, a reference phase can be constructed and the interesting phase can be directly extracted from a single interferogram without any carrier-removal operation. The proposed method shows a great high-speed property by the fact that it is approximately 4.5 times faster than a FTM and about 2 orders of magnitude faster than the LSI-SPS method. The phase extracted from a real interferogram of 156×156 pixels takes less than 1.28 ms with a typical desktop computer. These capabilities ensure high-speed phase measurements for dynamic phenomenon or moving objects.

2. Theory analysis

Generally, the intensity distribution of a carrier interferogram can be expressed as [1]

$$I(x,y) = A(x,y) + B(x,y)\cos\left[2\pi\left(\kappa_x x + \kappa_y y\right) + \phi_s(x,y)\right] \tag{1}$$

where A(x,y), B(x,y) and φ_s(x,y) are the background illumination, the modulation and the measured phase at pixel (x,y), κ_x and κ_y are the spatial carrier-frequencies along x-axis and y-axis direction, respectively. For simplicity, expression (1) can be rewritten as

$$I = A + B\cos[\Phi_R + \phi_s] \tag{2}$$

where $A = A(x,y)$, $B = B(x,y)$; and $\Phi_R = 2\pi(\kappa_x x + \kappa_y y)$ denotes the pure carrier-frequency phase at pixel(x,y) denominated here as the reference phase distribution. Referring to Fig. 1, for four adjacent pixels on the pattern, we assume that A, B, and φ_s have the same quantity in these adjacent pixels, while the reference phase Φ_R has different values. Thus, the intensities values, I_1 = I(x,y), $I_2 = I(x+1,y)$, $I_3 = I(x,y+1)$ and $I_4 = I(x+1,y+1)$ in these pixels are given by,

$$I_1 = A + B\cos[\phi_s + \Phi_{R1}] \tag{3a}$$

$$I_2 = A + B\cos[\phi_s + \Phi_{R2}] \tag{3b}$$

$$I_3 = A + B\cos[\phi_s + \Phi_{R3}] \tag{3c}$$

$$I_4 = A + B\cos[\phi_s + \Phi_{R4}] \tag{3d}$$

where Φ_{R1}, Φ_{R2}, Φ_{R3}, Φ_{R4} are the reference phase values in the four adjacent pixels. Subtracting the both sides of Eqs. (3a) and (3c) from Eqs. (3b) and (3d), respectively; we have

$$\begin{cases} I_1 - I_2 = B\psi_A\cos\phi_s - B\psi_B\sin\phi_s \\ I_3 - I_4 = B\psi_C\cos\phi_s - B\psi_D\sin\phi_s \end{cases} \tag{4}$$

With

$$\psi_A = \cos\Phi_{R1} - \cos\Phi_{R2} \tag{5a}$$

$$\psi_B = \sin\Phi_{R1} - \sin\Phi_{R2} \tag{5b}$$

$$\psi_C = \cos\Phi_{R3} - \cos\Phi_{R4} \tag{5c}$$

$$\psi_D = \sin\Phi_{R3} - \sin\Phi_{R4} \tag{5d}$$

From expression (4), we have

$$\frac{I_1 - I_2}{I_3 - I_4} = \frac{\psi_A\cos\phi_s - \psi_B\sin\phi_s}{\psi_C\cos\phi_s - \psi_D\sin\phi_s} \tag{6}$$