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A carrier removal method based on frequency domain self-filtering for interferogram analysis

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ABSTRACT

Based on interferogram frequency domain self-filtering methods, a simple, robust and effective carrier-removal approach for carrier interferogram analysis is proposed. The spatial carrier interferogram is firstly extrapolated to increase the frequency resolution, and a synthetic referencing interferogram distilled from the extrapolation interferogram with frequency domain self-filtering method. The carrier phase component is removed by subtracting the carrier phase extracted from the synthetic referencing interferogram with fast Fourier transform (FFT) method. Compared with existing carrier removal methods, numerical simulations and experiments, the proposed method is effective and accurate for suppressing the carrier-removal error caused by the digitization of the interferogram in the Fourier transform method (FTM) for carrier interferogram analysis.

1. Introduction

The Fourier transform method (FTM) of interferogram analysis is one of the most popular phase evaluation methods in a variety of optical interferometric measurements, and is also suitable for fringe projection profilometry. The FTM was first demonstrated by Takeda et al. [1] in 1982, and then developed to two dimensions by Bone et al. in 1986 [2]. Subsequently, many works about the theory and application of the FTM were published [3–7]. The notable advantage of the FTM is that it can extract phase information from a single interferogram by introducing carrier frequencies, thus it make the measurement dynamic and less sensitive to environmental perturbation, such as acoustics or other vibration. However, in practical applications, the fringe patterns are captured by 2D solid-state image sensors, such as CCD camera. The digitization of the interferogram data seriously distorts the retrieved phase and results in a considerable tilt error in the retrieved phase by introducing a carrier-removal error in the traditional spectrum-shifting method, as discussed by Nugent [8].

In the past two decades, many solutions have been presented to suppress the carrier-removal error. Bone et al. [2] tried to construct a carrier phase plane from an information-free region in the interferogram by the least-squares fit method to remove the carrier. Similarly, the least-squares-fit technique was used to obtain a pure carrier phase which is presented by a bilinear surface to describe the carrier component and noise was suppressed by phase iteration in [9]. Ferna and Kaufmann [10] subtracted a reference carrier phase which is calculated from an additional reference interferogram to directly remove the carrier phase in the spatial domain. However, this method requires an additional pure carrier-frequency interferogram

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which negates the advantage of single-shot measurement in the FT method as mentioned before. In addition, Li et al. [11] directly regarded the first derivative (average-slope) over a phase map as the carrier phase component. This method is fully automatic but the accuracy is dependent on the measured phase distribution. Ge [12] used the piezoelectric actuator to regulate the carrier-frequency values equal to an integral multiple of the sampling frequency by adjusts the inclination angle of the reference mirror. However, this device is complicated and time-consuming. Fan et al. [13] described a spectrum centroid method to suppress the carrier-removal error in the FT method. On the other hand, Zhang and Wu [14] used Zernike polynomials fitting to approximate the carrier phase distribution. Recently, Du et al. [15] reported a straightforward carrier-removal technique which is based on zero padding method, for simplicity, it is shorted as "ZPM" method. The carrier-frequency values with a small fraction are calculated from the extrapolation fringe by FFT algorithm. Then the measured phase is got by subtracting the pure carrier-frequency phase which is constructed by the calculated carrier-frequencies f_{0x} and f_{0y} in the spatial domain.

In this paper, we propose a simple, robust and effective carrier-removal approach for carrier interferogram analysis, which is based on interferogram frequency domain self-filtering methods. The frequency domain self-filtering enhances the periodic information of the interferogram by amplifying the peaks and attenuating the remaining areas. This method is more immune to the fractional part of carrier-frequencies f_{0x} and f_{0y} than FTM and ZPM. The proposed method is more than two orders of magnitude times faster than ZPM because the data quantity of it is much smaller. In this paper, we briefly denoted the proposed method as "SFM" for distinction. We firstly discuss the principle of the proposed method; secondly, some numerical simulations and optical experiments results are shown to demonstrate performance of the proposed SFM; finally, we conclude all the paper in the conclusion section.

2. Theory analysis

The deformed fringe pattern g(x,y) with linear-carrier is generally expressed as

$$g(x,y) = a(x,y) + b(x,y)\cos\left[2\pi(f_{0x}x + f_{0y}y) + \phi(x,y)\right] \tag{1}$$

where $a(x, y)$, $b(x, y)$ are the background and the modulation amplitude, respectively; f_{0x} and f_{0y} are the introduced spatial carrier-frequencies along x and y directions, respectively; $\phi(x, y)$ is the modulating phase. The carrier interferogram, $\cos\left[2\pi(f_{0x}x + f_{0y}y)\right]$, acts as a carrier information for recording the measured phase data but it will simultaneously introduce a carrier phase component, $2\pi(f_{0x}x + f_{0y}y)$, in the phase extraction procedure [16]. Hence the carrier phase component must be subtracted or removed from the overall phase distribution for evaluation of the phase of the measured phase component $\phi(x, y)$. Since the Fourier transform (FT) decomposes the image in terms of sinusoids, the fringe pattern with a periods in the spatial domain will have distinct peaks in the frequency domain. The carrier interferogram is processed with the FT in two-dimension, the first positive spectrum component $C(f_x, f_y)$ in the frequency domain isolated with a suitable spectral filter is

$$C(f_x, f_y) = F\{\frac{1}{2}b(x,y)\exp[\underbrace{j\phi(x,y)}_{irregular\ part} + \underbrace{j2\pi(f_{0x}x + f_{0y}y)}_{regular\ part}]\} \tag{2}$$

where $F\{\bullet\}$ denotes the FT operator. It is clear that the regular and irregular parts of the image can be separated in the frequency domain, and the measured phase component $\phi(x, y)$ is given by

$$\phi(x,y) = Unwrap\left\{\tan^{-1}\frac{Im\{F^{-1}[C(f_x,f_y)]\}}{Re\{F^{-1}[C(f_x,f_y)]\}}\right\} - 2\pi(f_{0x}x + f_{0y}y) \tag{3}$$

where $U(\bullet)$ denotes the phase unwrapping operator, the $\tan^{-1}(\bullet)$ denotes the arctangent operator, and the $F^{-1}\{\bullet\}$ denotes the inverse FT operator. However, the intensity of the fringe pattern is usually recorded by a solid-state image sensor such as CCD camera in practical applications thus the fringe pattern described in Eq. (1) usually should be further expressed as discrete form

$$g(m,n) = a(m,n) + b(m,n)\cos\left[2\pi\left(\frac{u_0}{M}m + \frac{v_0}{N}n\right) + \phi(m,n)\right] \tag{4}$$

where m, n are integer; M, N are the numbers of sampling points on the x, y directions, respectively; u_0 and v_0 are integer and the values of them are closed to the true carrier-frequency f_{0x} and f_{0y}, respectively. Corresponding, Eq. (2) is given by

$$C(\frac{u}{M}, \frac{v}{N}) = F\{\frac{1}{2}b(m,n)\exp[\underbrace{j\phi(m,n)}_{irregular\ part} + \underbrace{j2\pi(\frac{u_0}{M}m + \frac{v_0}{N}n)}_{regular\ part}]\} \tag{5}$$

Thus, the error introduced by the spectrum-shifting with traditional FTM is given by [17]

$$\Delta\phi(m,n) = 2\pi\left(\frac{\delta_x}{M}m + \frac{\delta_y}{N}n\right) \tag{6}$$