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Exact multi-shear reconstruction method with different tilts in spatial domain

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ABSTRACT

An improved zonal algorithm based on the multi-shear interferometry with different tilts is proposed to reconstruct two-dimensional wavefront exactly. The method allows large shear and high lateral resolution be achieved simultaneously. Due to environment vibration and mechanical misalignment, different tilt errors added in the measured wavefront will result in unknown and mismatch bias in the difference wavefronts. The effect of tilt errors in multi-shear method is analyzed and an improved zonal method is proposed to deal with tilt errors, which is easy to implement. Numerical simulations are executed and the results indicate that the improved algorithm is immune to tilt errors and has good noise suppression capabilities. In the experiment, we combine multi-shear method but using a Fizeau interferometer. The result demonstrates the effectiveness of the proposed algorithm.

1. Introduction

Wavefront measurement technology plays an increasingly important role in the fields of modern physics, astronomy, and biomedical engineering. Lateral shear interferometry (LSI) is a promising technique in the interferometry field for measuring optical components and systems [1]. It has diverse applications in multiple fields, such as in microscopic structure detection [2], freeform optics measurements [3,4], adaptive optics, and aberration measurements of optical systems [5–7]. Different from the ordinary wavefront interferometry such as Fizeau or Twyman–Green interferometer which measures wavefront directly, the LSI only measures the difference between original wavefront and the sheared copy wavefront. So how to recover wavefront from phase differences is the key in accurate measurement of LSI. A variety of two-dimensional (2D) wavefront reconstruction methods have been proposed from two phase difference maps in two orthogonal directions [8–29]. The existing reconstruction algorithms can be generally categorized into modal or zonal methods.

For the modal reconstruction method [8–16], the original wavefront is simply decomposed into a set of orthogonal basis functions, and the corresponding coefficients of basis functions can be obtained easily from the difference wavefronts in two orthogonal directions. The Zernike polynomials are orthogonal over the unit circle and the low-order terms are directly related to Seidel aberrations. Hence the Zernike polynomials have been commonly used as the basis functions to analyze the lateral shearing interferograms since they were first introduced by Rimmer and Wyant (1975) [9]. Liu (2003) proposed a difference Zernike polynomial fitting method [10]. This method was used in the extreme ultraviolet lithography wavefront measurement system [16]. The major problem of modal method is difficulty in obtaining high frequency components, because a small number of basis functions are often involved in the reconstruction. Although it is theoretically possible to obtain high frequency component, it needs a very large amount of basis functions which cost huge memory and computation time.

Different from modal method, the wavefront is estimated directly from the discrete values of the difference wavefronts at specific grid points in zonal reconstruction method [17–30]. It has the capability of obtaining all frequency components without any assumption or prior knowledge about the measured wavefront. Traditional zonal methods [17,18], e.g., Saunders method and Rimmer method, can reconstruct the wavefront exactly in theory, but they require the sample interval must be equal to the shear amount, which implies either low spatial resolution or small shear. Recently some LSIs that can achieve multiple shears in x/y directions were developed [20–23]. Most interesting is an electrically addressable element such as a spatial light modulator (SLM) to display gratings of different periods and orientations controlled by a computer. The main advantage of such a configuration is that a

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variety of different lateral and/or radial shears can be realized without the requirement of moving parts, which reduces error source compared with traditional variable shear interferometry. The multi-shear method can achieve large shear and high spatial resolution simultaneously. Large shear means a high signal to noise (SNR) ratio which can improve reconstruction accuracy in the existence of noise. In view of exact 2D wavefront reconstruction with multi shears, several improved zonal methods have been presented [23–27]. Elster and Weingärtner first proposed the double-shears algorithm to avoid spectral leaking problem [23] and subsequently Guo proposed a multi-shears algorithm to reconstructed wavefront exactly [24]. However, the effect of the tilt component in these algorithms is ignored. Because of environment vibration, mechanical movement and misalignment of the setup, the tilt component is different in multiple shearing interferograms when adopting multi shears to test a wavefront with LSI. Estimation errors are emerged in case multiple shearing interferograms are combined directly when the wavefront tilt differs between the shearing interferograms. Ding et al. proposed a method to remove tilt error in frequency domain [25]. The method originates from the natural extension method which has the restriction that the number of sampling points N is the product of shear amounts $S_1 \cdot S_2$ in corresponding directions [26]. To relieve the restriction of natural extension, we proposed the combined Saunders method to remove tilt error for one dimensional wavefront reconstruction [27].

In this paper, we propose a new multi-shear method in spatial domain for the reconstruction of 2D wavefront with tilt error. It allows large shear and high resolution of the reconstructed wavefront be achieved. The algorithm can eliminate tilt errors adaptively and has high accuracy recovery ability. Compared with the previous multi-shear methods [23–26], it does not need to adopt "natural extension" and hence the number of sampling points N are not subjected to the shear amount s. The sample aperture shape of wavefront is arbitrary, which is more flexible in practical measurement. The results of computer simulation and optical tests confirm the effectiveness and accuracy of the proposed algorithm.

2. Mathematical model for wavefront reconstruction from four interferograms

2.1. High spatial resolution zonal reconstruction method—SLE

To simplify the reconstruction procedure, we assume the test wavefront $\varphi(x, y)$ is sampled by a square grid with the size of $N \times N$ pixels. The sample resolution is one pixel and the shear amounts are chosen as multiple of sample resolution.

For the 2D wavefront reconstruction, we adopt two integer shear amounts S_x^1, S_x^2 for x direction measurement, and similarly two shear amounts S_y^1, S_y^2 for y direction measurement. As discussed in [28], for an exact reconstruction, the greatest common divisor(GCD) of S_x^1 and S_x^2, S_y^1 and S_y^2 should be 1, i.e., the shear amounts are coprime. The two difference wavefronts corresponding to x and y direction can be represented as D_x^j and D_y^j respectively as shown in Fig. 1, with j denoting the jth shearing for each shear direction.

The configuration of shearing interferometer based on a SLM is shown in Fig. 2. This is a conventional 4f system consisting of two lens L1 and L2 with focal length f. When the SLM locating in the Fourier plane displays a cosine grating along X or Y direction, we can obtain difference wavefront D_x along X direction or D_y along Y direction. By changing the period of grating which can be controlled by a computer, we can change the shear amounts S_x and S_y. The shearing interference occurs in the overlapped area of original wavefront and shear wavefront. The detailed descriptions can be found in [24,25].

Recently, Yin et al. proposed an exact zonal reconstruction method SLE to achieve high spatial resolution [30]. The basic idea is as follows:

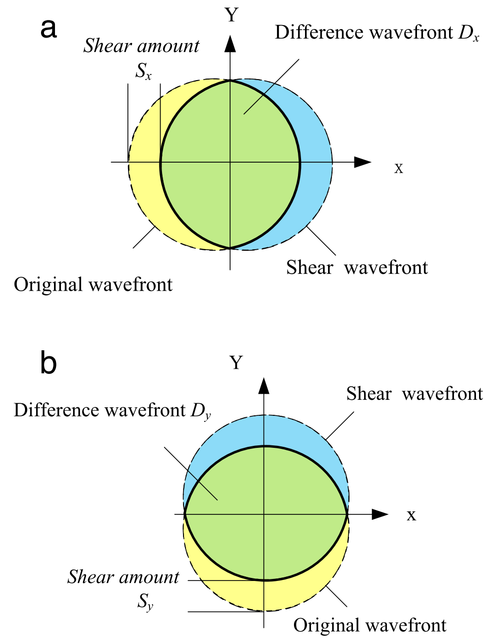

Fig. 1. Schematic diagram of lateral shearing region. (a) Difference wavefronts D_x along X direction, (b) difference wavefronts D_y along Y direction.

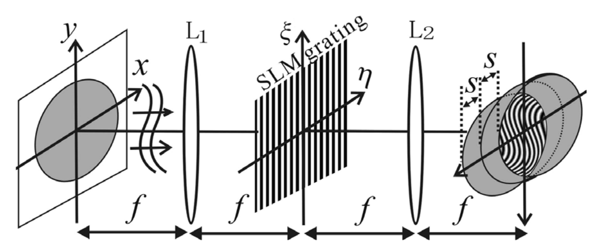

Fig. 2. Schematic arrangement of shearing interferometer based on a SLM. A lateral shearing interferogram along X direction is formed in the fringed area. S denotes the shear amount.

According to the point-to-point mapping relationship, the discrete test wavefront $\varphi(x, y)$ and the difference wavefronts, D_x^j and D_y^j, are related to each other by the matrix formulae

$$D_x^1(i_1, j_1) = \varphi(i_1 + S_x^1, j_1) - \varphi(i_1, j_1)\; i_1 \in [1, N - S_x^1];\; j_1 \in [1, N]. \tag{1a}$$

$$D_x^2(i_2, j_2) = \varphi(i_2 + S_x^2, j_2) - \varphi(i_2, j_2)\; i_2 \in [1, N - S_x^2];\; j_2 \in [1, N]. \tag{1b}$$

Combining Eqs. (1a) and (1b) into Eq. (2), a matrix formula can be obtained as

$$\begin{bmatrix} D_x^1 \\ D_x^2 \end{bmatrix} = A_x \varphi = \begin{bmatrix} A_{1x}^1 & & & 0 \\ & A_{1x}^2 & & \\ & & \ddots & \\ 0 & & & A_{1x}^N \\ A_{2x}^1 & & & 0 \\ & A_{2x}^2 & & \\ & & \ddots & \\ 0 & & & A_{2x}^N \end{bmatrix} \varphi. \tag{2}$$

where

$$A_{1x}^1(i_1, j_1) = A_{1x}^2(i_1, j_1) \ldots = A_{1x}^N(i_1, j_1) = \begin{cases} -1 & i_1 = j_1 \\ 1 & i_1 = j_1 - S_x^1 \\ 0 & \text{otherwise.} \end{cases}$$