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Two dimensional wavefront retrieval using lateral shearing interferometry

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ABSTRACT

A new zonal two-dimensional method for wavefront retrieval from a surface under test using lateral shearing interferometry is presented. A modified Saunders method and phase shifting techniques are combined to generate a method for wavefront reconstruction. The result is a wavefront with an error below 0.7λ and without any global high frequency filtering. A zonal analysis over square cells along the surfaces is made, obtaining a polynomial expression for the wavefront deformations over each cell. The main advantage of this method over previously published methods is that a global filtering of high spatial frequencies is not present. Thus, a global smoothing of the wavefront deformations is avoided, allowing the detection of deformations with relatively small extensions, that is, with high spatial frequencies. Additionally, local curvature and low order aberration coefficients are obtained in each cell.

1. Introduction

Several lateral shearing interferometer methods for wavefront reconstruction have been developed by many authors. Some lateral shear interferometers configurations include polarization [1], variable shear [2], cyclic shear [3], variable plate width [4], phase shifting using chessboard grating [5], cyclic shear with polarization [6,7], and other configurations [8–14].

Measuring lateral shear interferograms we obtain the phase difference between two identical aberrated wavefronts interfering with a mutual lateral displacement of one respect to the other. If the lateral shear of the two identical wavefronts is small compared with its pupil diameter, this phase difference is directly proportional to the wavefront slopes in the direction of the lateral shear. Many approaches had been used for wavefront retrieval from these phase difference or slope measurements. They can be classified in modal and zonal methods [15–18]. The modal approaches retrieve the wavefront by fitting a set of discrete phase difference measurements to a polynomial function, frequently obtained by a linear combination of a set of orthogonal basis functions. Most modal methods use Zernike polynomials as the basis functions [16,17,19–24]. Fourier transforms can also be used to retrieve the phase differences from a lateral shear interferogram. However, as proved by Freischlad and Koliopoulos [25], this method also filters out high spatial frequencies, as the polynomial fits over the whole wavefront, thus smoothing the retrieved wavefront. If small extent deformations of the wavefront are present, they will be eliminated.

There are many wavefronts or optical surfaces that have small local deformations with a high spatial frequency that cannot be represented with a global polynomial, mainly in the human eye. The solution in this case might be a zonal integration.

In general, zonal approaches do not use a polynomial fitting of the measured data thus, avoiding the filtering out of high spatial frequencies of the wavefront. Most zonal methods include direct phase and slope measurements to achieve wavefront reconstruction [15]. They also use different tools to measure phase and slopes, such as speckle interferometry, adaptive optics sensors, phase shift, and retrieve wavefront using Saunders method, interpolation and least squares fitting [26–42].

The original method [26] proposed by Saunders had to be implemented by an interpolation between two interference fringes, of the phase differences at the required and uniformly spaced sampling points.

The main advantage of the Saunders method is that the retrieved wavefront deviations are in principle exact, without any approximations, but it has a serious disadvantage, namely that these retrieved values are only at the corners of an array of square cells with a size equal to the magnitude of lateral shear.

To partially solve this disadvantage multiple shear magnitudes and also multiple shear directions had been tried to retrieve the wavefront [15,18,43–56].

We can use any lateral shear interferometer; the lateral shearing fringes are obtained by superimposing two identical wavefronts with a lateral displacement between them, called lateral shear. In lateral shearing interferometry, it is not necessary to have a reference wavefront because it interferes with an image of itself, laterally shifted [8–10,19]. From this difference between both shifted interferograms, wavefront can be reconstructed. Nevertheless, the wavefront tilt reconstruction is

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reduced to a constant proportional to the amount of shear [38] due to the nature of lateral shearing itself. Some authors have reconstructed tilted wavefronts using variable and multiple shears [38,54,56].

The size of the shear is an important issue. If it is a large shear, high frequency details in the wavefront could be attenuated or not detected [57], while the interferometer loses sensitivity with very small shears [24]. Usually, the amount of shear is chosen between 10% and 20% of the diameter of the wavefront [24,47]. In lateral shear interferometry, the fringes will represent the slopes of the wavefront along the shear direction [19], if the magnitude of the lateral shear is very small compared with the pupil diameter. Otherwise, the interferogram will represent the phase difference along the lateral shear interferogram, between the two wavefronts.

Here we propose, to our knowledge, a new method which combines a two-dimensional Saunders method and a phase shifting technique with a polynomial representation for the wavefront deformation on each square cell. Traditional Saunders method needs an interpolation between points all over the surface to obtain phase difference. Instead, here we use a Tilted T Three-Step algorithm [58] in order to measure phase difference between points disposed in a square arrangement avoiding errors due to interpolation and sign. The phase shifting analysis provides the values of the wavefront differences ΔW at every measured pixel in the pupil, but the values of W will remain unknown. However, they can be retrieved at the corners of a rectangular array of square cells, with the method described by Saunders [26]. It is worth to mention that any other phase shifting algorithm can be used.

Although Saunders and phase shifting methods have been used for wavefront reconstruction, they have never been combined with lateral shear interferometry in two orthogonal directions in the manner to be described here, where the retrieval of the wavefront deviations as well as the slopes (wavefront derivatives) at the corners of each square cell, can be obtained.

With the information of wavefront derivatives, we are able to avoid the so called shearing problem [48,57]. Instead of using another interferogram with a different amount of shear, we use the information provided by the wavefront slopes, which allows us the recovering of high spatial frequencies, using an interpolation inside every square cell. Our method uses a zonal integration with a polynomial representation at every cell. This process allows the reproduction of high spatial frequencies much higher than the pupil diameter but lower than the square cell size. As an additional bonus, the local curvature and low order aberration coefficients are obtained in each square cell.

Algorithms with square arrangements for wavefront retrieval in lateral shearing interferometers have been developed before [9,40,41]. To increase the number of sampling points, Nomura [34] and Yin [38], have used Saunders method with rotating shear and multiple or variable shears, respectively, for wavefront retrieval.

Therefore, our aim is to develop a simple method that only uses six interferograms (three for every orthogonal direction and computationally inexpensive) where the combination of lateral shear, phase shifting and improved Saunders method allows us to retrieve a wavefront using the information of derivatives avoiding the shearing problem. Once we have probed this method works, the next step would be apply it to aspherical surfaces and ophthalmic lenses with the goal of producing a generic optical test even for free form surfaces.

To test the validity of our method, we produced lateral shear synthetic interferograms of a well-known wavefront. This new procedure will be described in detail in the coming sections. It could be applied for optical testing even of aspherical surfaces, just varying the amount of shear it is possible to vary the number of fringes produced by this kind of surfaces [19].

2. Two-dimensional method description

2.1. Saunders method

This method determines the shape of a wavefront obtained from lateral shear interferometry. It consists of estimating the interference order

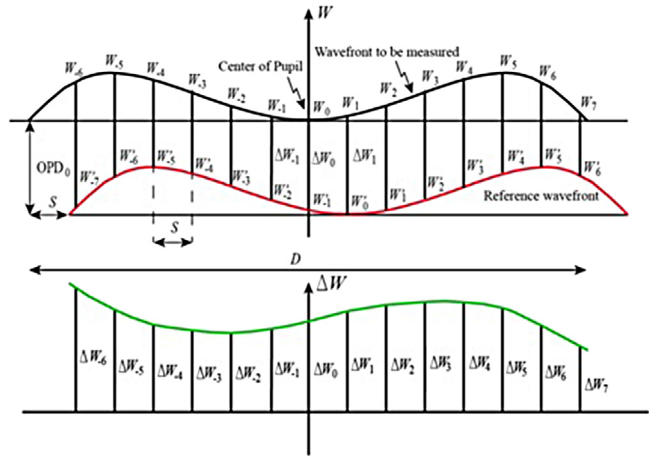

Fig. 1. Saunders method illustration. The wavefront is measured at selected points with the reference of the same wavefront displaced by an amount S called the shear.

at points spaced by a shear amount S along the diameter [34,38,58]. Traditional Saunders method evaluates ΔW at selected fringe positions and estimates ΔW's by the interpolation between fringes. Fig. 1 shows the way Saunders method works. In the figure, two wavefronts laterally shifted by an amount S are evaluated at the sampling points W_n.

It is an issue setting the value of S. As is seen in Fig. 2, the larger the amount of points measured, the more resolution is obtained from Saunders method, and that means a small S, relative to pupil diameter. Nevertheless, if S is very small, the effect of shearing is not significant and it loses sensitivity [24]. If S is too big, it is possible to lose information from high-frequency details [57] and the region of overlapping becomes too non-circular. We decided, for our simulations, to set $S = D/16.5$. A fraction of 16.5 is chosen to avoid points to fall exactly at the border, otherwise we would introduce errors due to the presence of diffraction in that region. This percentage chosen is within the valid range for the amount of shear [24,47].

According to Fig. 1, Saunders method consists on measuring from the interferogram the wavefront differences ΔW_n at a uniformly distributed distance S [34,38]. These are the differences between the wavefront to be measured and the reference wavefront. In our case, as graphically illustrated in Fig. 1, the center of the wavefront (center of pupil) is taken as a reference with a value $W_0 = 0$. If we establish that $W_1 - W_0 = \Delta W_1$ we can find expressions to obtain the values of W_n and W_{-n}. These expressions are

$$W_n = \Delta W_1 + \Delta W_2 + \cdots + \Delta W_{n-1} + \Delta W_n \tag{1}$$

$$W_{-n} = -(\Delta W_0 + \Delta W_{-1} + \cdots + \Delta W_{-(n-1)}) \tag{2}$$

where $n = 1, 2, 3, \ldots, N$.

The procedure to find the wavefront values at all sampled points is illustrated in Fig. 2. We have two matrices with points ΔW_{nx} and ΔW_{ny}.

Since wavefront tilt reconstruction is reduced to a constant in lateral shearing interferometry [38], we may also assume that the slopes at the center of the pupil are constant values and they can take the value of zero. The procedure to find the wavefront deformations at the sampled points as illustrated in Fig. 2, is carried out by scanning in rows the interferogram with the shear along the direction x (columns for y direction). We start at the center assuming, as we pointed out before, that both the wavefront deviations and the slopes are zero at the origin. Then, we use the above equations scanning along the x and y axes until we reach the last point.

First, Eqs. (1) and (2) are applied along x and y direction for central reference lines (central row for x and central column for y), obtaining