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Three-step shift-rotation absolute measurement of optical surface figure with irregular shaped aperture

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ABSTRACT

The absolute testing technique has been widely employed in sub-nanometer optical surface metrology, we have presented a generalized shift-rotation absolute measurement method for high-numerical-aperture spherical surfaces (Yang et al., 2017). In this paper, a simple and effective three-step shift-rotation absolute testing technique for optical surface figure with irregular shaped aperture is presented. The test surface is tested in an original, a rotational and a shift position. Based on the orthonormal polynomials over irregular shaped aperture, the absolute figure of the test surface is separated from the reference surface errors by the two measurement difference data. Simulation results presented in the paper indicated the validity of the three-step shift-rotation absolute measurement method. The measurement results show a good agreement with the results measured by commercial profiler. The novel three-step shift-rotation absolute testing technique is a promising method to measurement the optical flat and spherical with the irregular shaped aperture.

1. Introduction

Optical methods are non-contacting and highly accurate metrological tools which have been used for optical and mechanical components measurement [1–4]. The optical elements with irregular shaped aperture are widely used in some special optical systems and play an important and irreplaceable role. In the large telescope system, such as California extremely large telescope (CELT) [5] and the large sky area multi-object fiber spectroscopic telescope (LAMOST) [6], the primary mirror is a mosaic of hexagonal optical element. In the high power laser systems, such as National Ignition Facility (NIF) [7,8] and SG-III laser facility [9,10], the optical elements with square and rectangular aperture are always involved. The optical systems, which contain cylindrical lens, are usually have rectangular aperture [11,12]. In space optics and head-mounted display system, freeform surfaces with irregular shaped aperture offer more degrees of freedom to the optical design process [13,14]. Moreover, polygon optical element and Sic reflector with an irregular boundary are irreplaceable elements in space camera system [15]. Just like the optical surface with circular aperture, the optical surface with irregular shaped aperture usually tested by a phase shifting interferometer, the surface figure can be obtained from the measurement wavefront data. Zernike polynomials are used in optical surface testing for their orthogonality over a unit circular aperture and representation of classical aberrations in optical system [16]. For the optical surface with noncircular aperture, Zernike polynomials are neither orthogonal nor represent classical aberrations [17]. Fortunately, based on Zernike polynomials over a unit circular aperture, polynomials that are orthogonal over noncircular aperture are obtained by the process of orthogonalization. Analytical expressions of orthogonal polynomials over annular, hexagonal, elliptical, rectangular, square, and olivary aperture are obtained in literatures [18–26]. Recently, expressions of orthogonal polynomials over general aperture shapes have been developed [27–29].

The absolute testing technique has been widely employed in sub-nanometer optical surface metrology to calibrate the reference surface deviation. The two sphere absolute testing and random ball averaging method have been used in spherical surface figure measurement with a circular aperture [30,31]. The three flat testing and their improved method gradually used in plane surface measurement by the single line to the entire surface [32–34]. The conjugate differential method was adopted to measure the optical flat and cone mirror with rectangular or square aperture [35–37]. A lot of valuable work for shift rotation method has been done to measure the optical flat and spherical surface [38–41]. We have proposed a generalized shift-rotation

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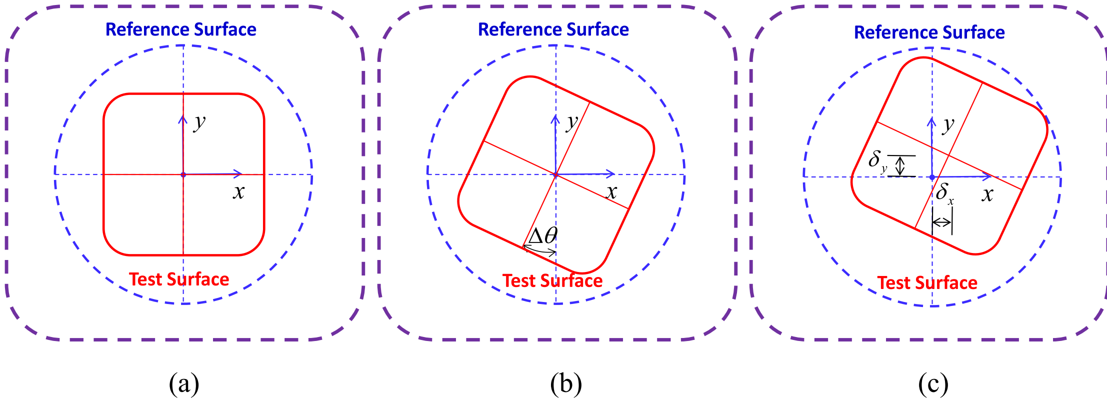

Fig. 1. The measurement progress. (a) The basic position. (b) The rotation position. (c) The translated position.

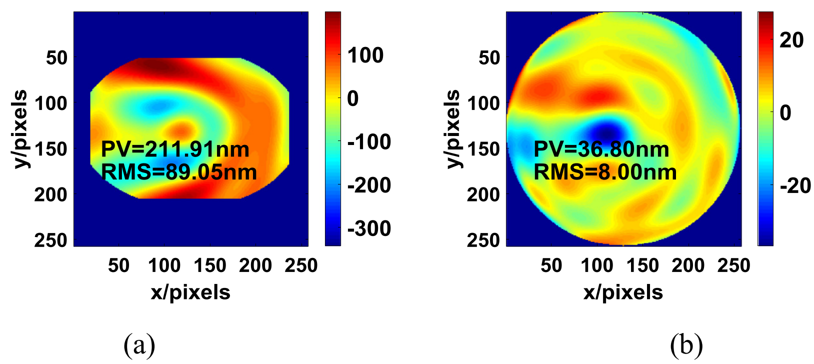

Fig. 2. The figure of test surface over the irregular shaped aperture and reference surface shape over the unit circular aperture. (a) The figure of the test surface. (b) The figure of the reference surface.

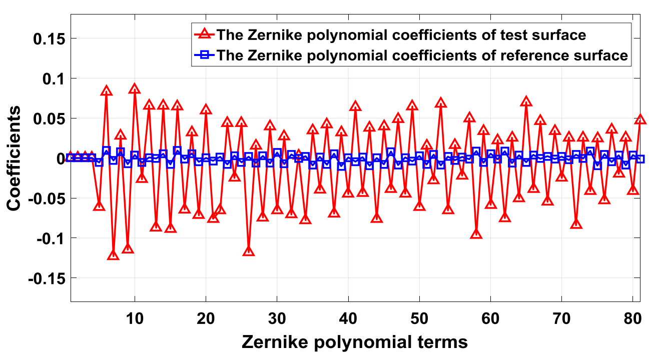

Fig. 3. The corresponding coefficients of Zernike polynomials of test and reference surface.

absolute measurement method for high-numerical-aperture spherical surfaces [42]. To the best of our knowledge, the wavefront reconstruction process in full-aperture surface absolute measurement method cannot reconstruct the wavefront with irregular shaped aperture. So, almost the absolute testing technique cannot measure the optical surfaces with irregular shaped aperture.

This paper presents a novel three-step shift-rotation absolute testing technique using orthogonal polynomials over irregular aperture shapes, which could be used to measure the optical flat and spherical surfaces which have the irregular shaped aperture. Numerical simulation with random noise during the measurement and experimental results confirm the feasibility of the three-step shift-rotation absolute measurement method. The numerical orthogonal transformation process for polynomial over irregular aperture and the absolute measurement process are discussed in Section 2. Numerical simulations and the experimental results are shown in Sections 3 and 4, respectively. Section 5 is the error analysis and some discussions of our three-step shift-rotation absolute measurement method. Some concluding remarks are drawn in the last section.

2. Principle

2.1. Orthonormal polynomials over irregular shaped aperture

The optical elements usually have a circular aperture for the optical system generally have an axis of rotational symmetry. Zernike polynomials $Z_n^m(\rho,\theta)$ are widely used in optical surface testing for their orthogonality over a unit circular aperture and representation of classical aberrations in the optical system, which can be written as [16]:

$$\begin{cases} Z_n^m(\rho,\theta) = \left[\dfrac{2(n+1)}{1+\delta_{m0}}\right]^{\frac{1}{2}} R_n^m(\rho)\cos(m\theta) \\ R_n^m(\rho) = \displaystyle\sum_{s=0}^{(n-m)/2} \frac{(-1)^s (n-s)!}{s!\left(\frac{n+m}{2}-s\right)!\left(\frac{n-m}{2}-s\right)!}\rho^{n-2s} \end{cases} \quad (1)$$

where (ρ,θ) is the polar coordinate over the unit circular aperture, n and m are positive integers including 0 and $n-m>0$, δ_{ij} is a Kronecker delta. The Zernike polynomials are orthogonal over a unit circular aperture according to:

$$\begin{cases} \dfrac{1}{\pi}\displaystyle\int_0^1\int_0^{2\pi} Z_n^m(\rho,\theta) Z_{n'}^{m'}(\rho,\theta)\rho\, d\rho\, d\theta = \delta_{mm'}\delta_{nn'} \\ \displaystyle\int_0^{2\pi}\cos(m\theta)\cos\left(m'\theta\right)d\theta = \pi\left(1+\delta_{m0}\right)\delta_{mm'} \\ \displaystyle\int_0^1 R_n^m(\rho) R_{n'}^m(\rho)\rho\, d\rho = \frac{1}{2(n+1)}\delta_{nn'} \end{cases} \quad (2)$$