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Non-overlap subaperture interferometric testing for large optics

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ABSTRACT

It has been shown that the number of subapertures and the amount of overlap has a significant influence on the stitching accuracy. In this paper, a non-overlap subaperture interferometric testing method (NOSAI) is proposed to inspect large optical components. This method would greatly reduce the number of subapertures and the influence of environmental interference while maintaining the accuracy of reconstruction. A general subaperture distribution pattern of NOSAI is also proposed for the large rectangle surface. The square Zernike polynomial is employed to fit such wavefront. The effect of the minimum fitting terms on the accuracy of NOSAI and the sensitivities of NOSAI to subaperture's alignment error, power systematic error, and random noise are discussed. Experimental results validate the feasibility and accuracy of the proposed NOSAI in comparison with wavefront obtained by a large aperture interferometer and stitching surface by multi-aperture overlap-scanning technique (MAOST).

1. Introduction

The accuracy, reproducibility and efficiency of the measurement techniques and systems need to be improved with increasing demands from the optical manufacturing. Subaperture stitching interferometry plays an important role in large aperture and large NA surface metrology, including planar, spherical, aspherical and even free-form surfaces, because it can extend the lateral measurement ranges while enhancing the lateral and vertical resolutions.

In the early models of stitching interferometry, there was no overlap between subapertures [1]. In order to improve the stitching accuracy and achieve high spatial resolutions, multi-aperture overlap-scanning technique (MAOST) was proposed for high precision large aperture measurement [2,3]. With MAOST, a large optical surface is tested by an overlap-scanning sequence with a small aperture interferometer and then the surface of the full aperture is reconstructed through the consistency of data in overlapping regions. One reconstruction approach was to simultaneously make the sum of the squared differences for all overlapping data minimum to reduce the accumulation error of stitching [4]. In order to improve the accuracy, compensation using a reference mirror [5] or an iterative algorithm [6] have been proposed. These approaches have been used for large area measurement of planar [7], cylindrical [8], spherical [9] and aspherical [10] surfaces. The optimal overlap area for these methods has been shown to be 30% of the subaperture area [11]. Thus the number of subapertures will increase with the size of optics. For example, for a 400×800 mm optical flat, 66 subapertures at 30% overlapping ratio are needed if a 100 mm interferometer is used. Furthermore to ensure accuracy, the environment and the entire measurement system must be stable during scanning of these 66 subapertures making it difficult to be used in a workshop environment [12]. Hence the need arises for fewer subapertures for reduced environment uncertainty and reduced errors in the stitching process.

Two methods namely the Kwon-Thunen and Simultaneous fit [13,14] reconstruct the full aperture using Zernike polynomial with non-overlapping subapertures but with some differences. In the Kwon-Thunen method, the subaperture wavefront and full aperture wavefront are both fitted by a Zernike polynomial and the polynomial coefficients are solved by minimizing their difference. This method is more sensitive to the alignment errors of the subapertures. In the Simultaneous fit approach, the first three Zernike terms, namely piston, x-tilt and y-tilt, of each subaperture are fitted independently, which can avoid their impact on the fitting of higher-order terms and with better computational efficiency. Though both methods suffer from the problem of describing some wavefronts with localized irregularities with the Zernike polynomials, they have sufficient precision for testing relative smooth surfaces, such as planar surfaces. The greatest advantage of this kind of method is the reduction in the number of subapertures. Using the same optical flat with the size of 400×800 mm as an example, the Kwon-Thunen or Simultaneous fit method, needs to scan about 32 subapertures saving more than 50% scanning time. Furthermore, for fewer scanning subapertures, the

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start-up and stop times are also reduced greatly, thus reducing mechanical errors.

This paper will test the rectangular optical flats with large scales on the machine tool table in workshop by non-overlap subaperture interferometric testing method (NOSAI). It introduces the principle of NOSAI and gives the revised Zernike polynomial suitable for rectangular shape. The effect of the minimum number of fitting terms on the accuracy of NOSAI and the sensitivities of NOSAI to subaperture alignment error, power systematic error, high frequency noise, higher-order terms of fitted surface and subapertures distribution are discussed. The experimental system is established with a dynamic interferometer as the measuring instrument. Experiments verified the feasibility and accuracy of NOSAI. In Section 2, the basic principle of NOSAI and square Zernike polynomials is described. In Section 3, a numerical simulation is given to test the validity and the sensitivities of the method. In Section 4, experimental verification of NOSAI is shown.

2. Principle of NOSAI

Assuming that the translation between subapertures is rigid and excluding geometrical errors from the mechanical platform, the measured wavefront of subapertures should be consistent with the full aperture wavefront in theory if the interferometer is correctly calibrated. According to this principle, the fitting coefficients of piston, tip and tilt terms of subapertures and the fitting coefficients of the full aperture wavefront can be solved simultaneously. NOSAI does not involve positional relationships between subapertures, which mean that an arbitrary distribution of the subapertures is acceptable, even without overlap.

The wavefront of the full aperture surface can be expressed as,

$$W(x,y)=\sum_{i=4}^{N} m_i Z_i(x,y) \tag{1}$$

where $W(x,y)$ is the fitted wavefront of the full aperture and (x,y) is its coordinate, $Z_i(x,y)$ is the ith fitting polynomial, m_i is its coefficient, N is the total number of polynomial terms. The coefficients of the first three terms (piston, tip and tilt) are not related to the surface shape and set to zero in Eq. (1).

If there is only rigid translation between measured subaperture and full aperture wavefronts, then the residue error R can be calculated as

$$R=\sum_{k=1}^{M}\left[\left(w_k(x,y)+n_{k1}+n_{k2}x+n_{k3}y-\sum_{i=4}^{N} m_i Z_i(x,y)\right)Q_k(x,y)\right]^2 \tag{2}$$

where M is the total number of subapertures, $w_k(x,y)$ is the measured wavefront of the kth subaperture, $Q_k(x,y)$ is the corresponding weight value of the kth subaperture at point (x,y) to separate the useful sampling points ($Q_k(x,y)$=1) and the useless sampling points($Q_k(x,y)$=0). The alignment coefficients of kth subaperture relative to the full aperture is $n_k=(n_{k1},n_{k2},n_{k3})^{\mathrm{T}}$ in $X_k=(1,x_k,y_k)$.

The fitting coefficients of all subapertures are denoted as $S_n=(n_1,n_2,\dots,n_M)^{\mathrm{T}}$, and the subaperture coordinates are $X=(X_1,X_2,\dots,X_M)$, the fitting coefficients of the full aperture are $S_m=(m_4,m_5,\dots,m_N)^{\mathrm{T}}$, the Zernike polynomial terms $Z=(Z_4,Z_5,\dots,Z_N)$, the subaperture wavefronts $W=(w_1,w_2,\dots,w_M)$ with their weights $Q=(Q_1,Q_2,\dots,Q_M)$, then Eq. (2) can be rewritten as

$$R=\sum_{k=1}^{M} Q(W-HV)^2 \tag{3}$$

where$H=[ZX]$, $V=[S_mS_n]^T$.

By minimizing$R$, the least squares estimate of V is,

$$\hat{V}=(H^TQH)^{-1}H^TQW \tag{4}$$

Thus, the fitting coefficients of full aperture wavefront and alignment coefficients of each subaperture can be obtained simultaneously through a global coordinate synchronization. Thus the impact of accumulation error and local measurement errors can be reduced.

3. The measurement scheme for rectangular optical flats

For the rectangular plane surface, we attempt to program a general measurement scheme with the appropriate polynomial and the optimized subaperture distribution. This is more valuable for further application.

3.1. Square Zernike polynomial

Zernike polynomials are often used to express the wavefronts since the polynomial terms with the same forms as the aberrations observed in optical testing. It should be noted that the Zernike polynomials are orthogonal only over the unit circle. It is convenient to represent a square or rectangular aperture with 2D set of Legendre polynomials for its orthogonality, but it does not include the useful rotationally-symmetric terms, in particular, “power” term, i.e. (x^2+y^2) [15]. In ISO/TR14999, orthogonal square Zernike polynomials are built, which have the same forms as the corresponding classical Zernike polynomials but with different coefficients [16]. Due to the complex interaction between the square area of definition and the rotationally symmetrical basis of these functions, there is no simple formula for the polynomial coefficients. They can only be described term by term using the following expression,

$$\sum\{P_n(r)\cos(m\theta)\}\ \text{and}\ \sum\{Q_n(r)\sin(m\theta)\} \tag{5}$$

where (r,θ) are polar coordinates, $r=\sqrt{x^2+y^2}$. The range of x and y is [-$\sqrt{2}$,$\sqrt{2}$], which means half diagonal of the area should be equal to one. $P_n(r)$ and $Q_n(r)$ denote polynomials in the variable “r” and the order of the function is $n+m$, where n, m are non-negative integers.

The first 11 square Zernike polynomials based on polar symmetry are given in Table 1. Theoretically, the fitting accuracy can achieve 10^{-15} by using appropriate terms.

3.2. Compare with normal Zernike polynomial

The most common fitting principle for the rectangular surface is using polynomials which are derived from Zernike polynomials and made orthogonal over corresponding apertures. This change should be fully transparent to the fitting process. A rectangular wavefront is simulated as Eq. (6) and fitted using two different polynomials, one is the orthogonalized Zernike polynomials, the other is the square Zernike polynomials. RMS of the residual surface error is used to illustrate the fitting accuracy. It could get 10^{-4} when using the orthogonalized Zernike polynomials (Fig. 1(a)) and get 10^{-14} when using the square Zernike polynomials (Fig. 1(b)). Both of these two polynomials could get well precision in the simulation with no error introduced. The

Table 1
Square Zernike polynomials [16].

Term	Order ($n+m$)	n	m	Polynomial
Z_1	0	0	0	1
Z_2	2	1	1	$r\cos\theta$
Z_3	2	1	1	$r\sin\theta$
Z_4	2	2	0	$2r^2-2/3$
Z_5	4	2	2	$r^2\cos 2\theta$
Z_6	4	2	2	$r^2\sin 2\theta$
Z_7	4	3	1	$r(15r^2-7)\cos\theta/5$
Z_8	4	3	1	$r(15r^2-7)\sin\theta/5$
Z_9	4	4	0	$2(315r^4-240r^2+31)/105$
Z_{10}	6	3	3	$r^3\cos 3\theta+3r(13r^2-4)\cos\theta/31$
Z_{11}	6	3	3	$r^3\sin 3\theta+3r(4-13r^2)\sin\theta/31$