



Testing aspheric in interferometric setups: removal of adjustment errors from measurement result

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Received 6 June 2004; received in revised form 30 July 2004; accepted 31 August 2004

Abstract

We demonstrate experimentally a valid method to remove the adjustment errors from wavefront aberration in interferometric setups when measuring convex aspheric surface with asymmetric errors. By comparing the coefficients of Zernike polynomials of the first measurement with that of the second measurement after rotating the aspheric to 180°, we can decide whether there are adjustment errors in measured wavefront and remove them. We have successfully tested a 100-mm diameter convex surface of errors 234 nm P-V after removing adjustment errors. It is believed that the method may greatly improve the measurement accuracy, and simplify the adjustment of the interferometric setups for an aspheric surface with strong asymmetric errors.

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PACS: 06.20.D; 06.02.D; 07.60.L

Keywords: Error theory; Measurement theory; Interferometer

1. Introduction

One can usually evaluate aspheric surfaces by means of interferometric techniques. In which an ideal aspheric wavefront fitting the surface under test is generated by applying either a compensating

system [1] or a matrix. The matrix is an optical element that generates the appropriate aspheric wavefront and bears a reference surface of opposite aspherical shape [2,3]. These methods allow one to achieve great accuracy if no adjustment errors during the course of the adjustment are ensured. However, there is no direct method to decide whether there are adjustment errors in most practical cases. Some authors [4–6] have studied the errors and have even devised ways to solve it

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by ray tracing of the entire interferometer system with simulation of the misalignment effects. However, this approach is limited to measuring the aspheric surfaces with symmetric errors. For those surfaces with asymmetric errors, shape errors could be interpreted as adjustment errors leading to overcompensation. Especially for those with strong asymmetric errors, this approach tends to lead to large uncertainty in measured wavefront.

We present a new approach to the calculus of the errors caused by misalignment based on Zernike polynomials which works well for a surface with asymmetric errors. By using a 5-axis Mount with accurate self-centering element holder, a pinhole and a micrometer, we duplicate the tilt and decenter with the necessary accuracy after rotating the aspheric 180°. Certainly, the technique to duplicate decenter only works well for weak aspherics (small deviations from sphere). However, it is very easy and costless compared with other techniques. We obtain two interferograms which include almost the same errors caused by misalignment. By comparing these two sets of zernike polynomials obtained from two different measurement results, we can decide whether there are errors caused by misalignment in the measured wavefront and then remove them. This method may greatly improve the measured accuracy for an aspheric with asymmetric errors, especially for that with strong asymmetric errors, and simplify the adjustment of the interferometric setups.

2. Wave front expression by using of zernike polynomials

Adjustment of the interferometric setup can be time-consuming, since five degrees of freedom need to be balanced: tilt and decenter of the aspheric surface in two directions and defocus, especially since some of the adjustment errors may compensate some aberration inherent in the aspheric surface with asymmetric errors under test. We can divide the adjustment errors into three kinds: one caused by decenter of the aspheric surface, one caused by tilt and another caused by defocus.

We have found it appropriate to approximate the measured wavefront by summation of ortho-

normal zernike polynomials up to 36 terms. They easily interface with ray tracing program to determine and eliminate the influences of the actual adjustment errors on the measured wave front [7]. Let $w(r, \theta)$ be an approximation of the measured wavefront $W(r, \theta)$:

$$\begin{aligned} W(r, \theta) &\cong w(r, \theta) \\ &= \sum_{j=1}^N A_j U_j(r, \theta) \\ &= \sum_{n=0}^K \sum_{m=-n}^n R_n^m(r) a_n^m \begin{cases} \sin \\ \cos \end{cases} m\theta \end{aligned} \quad (1)$$

with A_j as coefficients of Zernike polynomials and a_n^m as the coefficients associated with a particular term; j is the number of the polynomial term; n and m are the indices of Zernike polynomials; The sine function is used for $m < 0$ and the cosine function for $m > 0$. When testing, we adjust the aspheric surface to the best condition by observing the interferometric fringe. Small defocus often introduces focus and spherical aberration into the result which may compensate spherical aberration inherent in the aspheric surface. However, the spherical aberration can be calculated according to the defocus power which can be gotten in the measurement result, since the combination between the focus and different orders of spherical aberration is linear [8]. Usually, this requires an aspheric with certain vertex radius. Here, we mainly discuss the adjustment errors caused by decenter and tilt in my paper. Decentering and tilting the aspheric surface by only a small amount mainly introduce coma into the measurement result which may compensate the coma inherent in the aspheric surface. We may not calculate the coma except that the amount of the decenter and tilt is gotten. In practice, however, it is difficult to obtain the accurate amount of decenter and tilt. Taking into account that mainly Zernike terms with $m = \pm 1$ [4], as shown in Table 1, will arise when there is coma, only these polynomials need to be evaluated. The coefficients of these terms include two parts, one corresponding to coma introduced by decentering and tilting the aspheric surface, the other one corresponding to coma inherent in the surface. If we can measure the aspheric surface

Table 1
Zernike polynomials with $m = \pm 1$

$U_6 = (3r^3 - 2r)\sin \theta$	$U_7 = (3r^3 - 2r)\cos \theta$
$U_{13} = (10r^5 - 12r^3 + 3r)\sin \theta$	$U_{14} = (10r^5 - 12r^3 + 3r)\cos \theta$
$U_{22} = (35r^7 - 60r^5 + 30r^3 - 4r)\sin \theta$	$U_{23} = (35r^7 - 60r^5 + 30r^3 - 4r)\cos \theta$
$U_{33} = (126r^9 - 280r^7 + 210r^5 - 60r^3 + 5r)\sin \theta$	$U_{34} = (126r^9 - 280r^7 + 210r^5 - 60r^3 + 5r)\cos \theta$

So, the coefficients of the terms with $m = \pm 1$ of these two measurements can be expressed as Table 2.

twice by rotating it to 180° without changing tilt and decenter, the coma resulted by decenter and tilt does not change after rotation, while the coma inherent in the surface is opposite due to

$$\begin{aligned} \sin \theta &= -\sin(\theta + 180^\circ), \\ \cos \theta &= -\cos(\theta + 180^\circ). \end{aligned} \tag{2}$$

Adding these two set of coefficients, respectively, we can get the values corresponding to coma introduced by adjustment. Then remove it from measured wavefront. Certainly, it is in general not possible to measure the aspheric surface twice by rotating it to 180° without changing tilt and decenter. However, we can control the variation of tilt and decenter after rotation with the accuracy to satisfy the requirement for the measurement by using some special approaches. In our experiment, tilt may be controlled to a quite accuracy by using a mechanical reference, and decentering may be controlled by in principle the null test condition. Although, the decentering is limited for weak aspherics, it is a very easy and cheap technique compared with other methods. If we want to remove adjustment errors for those aspherics with large deviations, we must use other techniques to duplicate the positions of the aspherics after rotation, such as using fiducial marks [9].

3. Experiment and data

We have designed and fabricated an interferometric setup with a computer-generated hologram fabricated onto a sphere reference surface to measure convex surface shown in Fig. 1. In this system, the area of dimensions between the pinhole and the first lens is 588 mm, the air gap between the reference surface and the aspheric is set at 10 mm, and the convex aspheric being tested is an elliptic mirror with 100 mm in diameter and 500 mm of vertex radius. The CGH for test the aspheric, fabricated on the sphere reference surface of the test plate with 11f/50 by using a laser direct writer [10,11], requires 160 rings, with spacing varying from 4000 to 200 μm . The radius of the reference is set at 500 mm to keep the orders separated by 2 m rad. We use He–Ne laser (632.8 nm) as the light source. In order to remain the same adjustment errors after rotating the convex surface to 180° , we mount the aspheric element into the self-centering element holder, and use a micrometer with 1 μm accuracy to monitor the tilt of the aspheric surface by making its indicating needle perpendicular to the edge of the front surface of the mount as shown in Fig. 2. Here, the tilt variation of the aspheric is equal to that of the

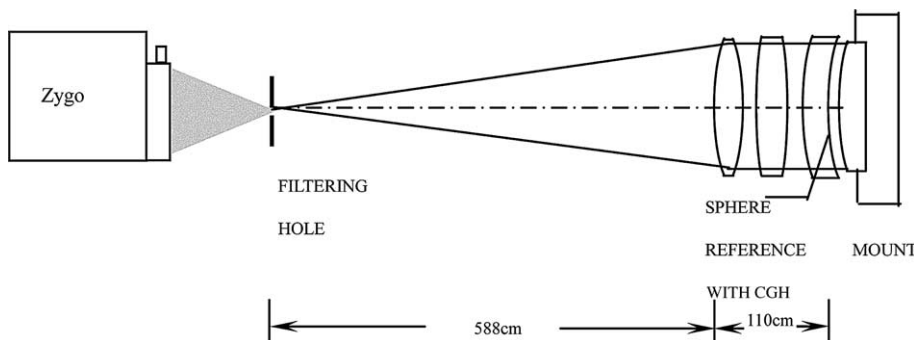


Fig. 1. Layout for measuring convex surface by using a test plate with CGH.

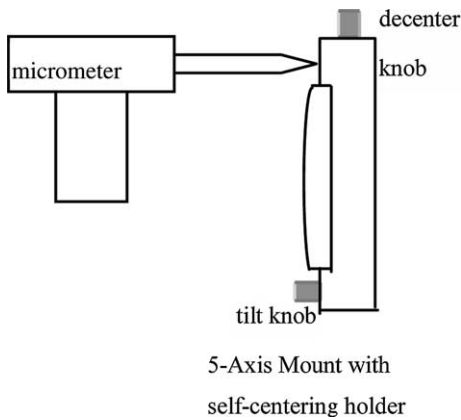


Fig. 2. Layout for adjustment.

front surface of the mount as they are fixed together. Duplicating the tilt of the mount means to duplicating that of the aspheric. Before rotation, we null the fringes best by adjusting the knobs on the mount and record the numerical reading of the micrometer. A mask is added on the screen which may be completed in interferometric software. The fringes should completely full the mask without vignetting. Then we rotate the holder to 180° . After rotation the tilt may double; the decenter may change due to the imperfect excircle of the aspheric element, because it can re-

sult in noncoincidence between two centers of the excircle of the aspheric element and the mechanical rotation axis of the holder. First, we adjust the X/Y tilt knobs on the mount until the numerical reading of the micrometer is the same as that recorded before rotation. It means that the tilt may be duplicated after rotation and the accuracy may be controlled within 0.001° corresponding to the accuracy of the micrometer. Second, we duplicate the decenter by adjusting the X/Y decenter knobs on the mount to make the fringes completely to full the mask again. The reason for this is that the reflected beam from the aspheric may be truncated by the small pinhole due to the change of decenter after rotation, which will result in the fringes imperfect in the mask. We simulate this method in optical design software Zemax by using the parameters of our system, in which the pinhole is 0.3 mm in diameter, and the tilt variation is $\pm 0.001^\circ$ after rotation. The decenter variation resulted in is $\pm 18 \mu\text{m}$ and the tolerance of measured wavefront is 0.04λ . Although, the decentering cannot be controlled to a quite accuracy using this method, it is enough to measure weak aspherics. What is more, it is easy and costless.

We measured a 100-mm clear-aperture aluminium aspheric produced by diamond-cutting twice by rotating it to 180° in our optical system. The

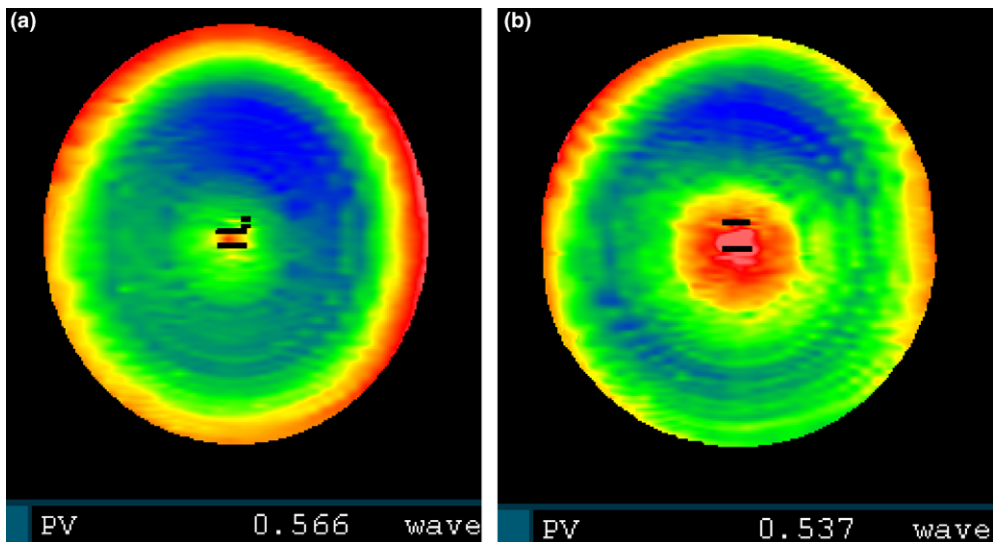


Fig. 3. (a) Phase map of the aspheric under test. (b) Phase map of the aspheric under test rotated to 180° .

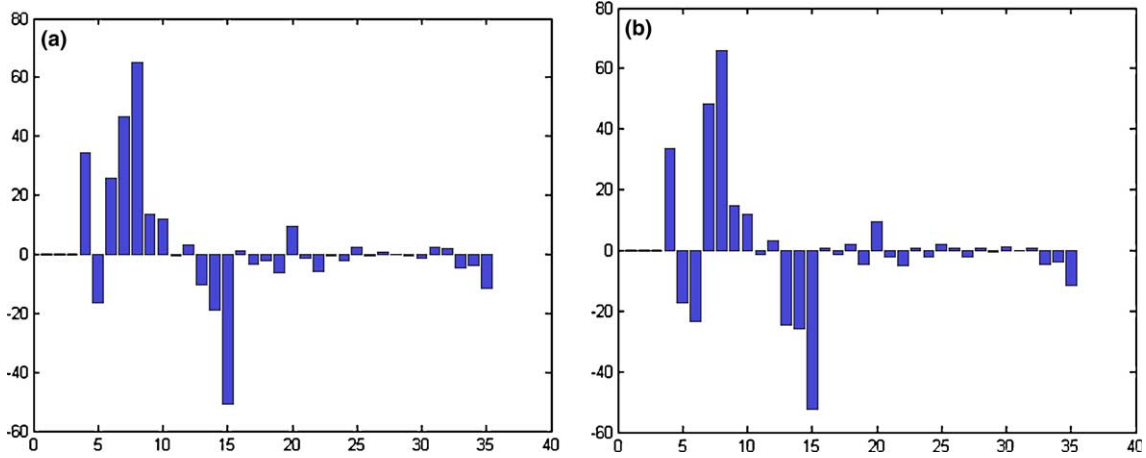


Fig. 4. The coefficients for Zernike polynomials positioned according to their Zernike orders: (a) corresponding to Fig. 3(a) and (b) corresponding to Fig. 3(b).

Table 2
Coefficients of Zernike polynomials with $m = \pm 1$

Before rotation	After rotation
$A_6 = a_2^1 = A_{6-1} + A_{6-2}$	$A_6 = a_{2-1}^1 = A_{6-1} - A_{6-2}$
$A_7 = a_2^{-1} = A_{9-1} + A_{9-2}$	$A_7 = a_2^{-1} = A_{7-1} - A_{7-2}$
$A_{13} = a_3^1 = A_{13-1} + A_{13-2}$	$A_{13} = a_3^1 = A_{13-1} - A_{13-2}$
$A_{14} = a_3^{-1} = A_{14-1} + A_{14-2}$	$A_{14} = a_3^{-1} = A_{14-1} - A_{14-2}$
$A_{22} = a_4^1 = A_{22-1} + A_{22-2}$	$A_{23} = a_4^1 = A_{23-1} - A_{23-2}$
$A_{23} = a_4^{-1} = A_{23-1} + A_{23-2}$	$A_{23} = a_4^{-1} = A_{23-1} + A_{23-2}$
$A_{33} = a_5^1 = A_{33-1} + A_{33-2}$	$A_{33} = a_5^1 = A_{33-1} + A_{33-2}$
$A_{34} = a_5^{-1} = A_{34-1} + A_{34-2}$	$A_{34} = a_5^{-1} = A_{34-1} + A_{34-2}$

23, 33, 34 are different while the others almost remain the same.

According to the data presented in Fig. 4 and Table 2, we can calculate the coefficients for Zernike polynomials resulted by the adjustment errors. Subtracting the calculated values from the coefficients for Zernike polynomials of the aspheric surface given in Fig. 4, respectively, a distortion correction for the final wave front with errors of 234 nm P-V is obtained. It is about 0.2λ smaller

wave-front errors of the aspheric consist mainly of spherical aberration, primary astigmatism and coma as shown in Fig. 3. The wavefront errors are 358 nm P-V before rotation and 340 nm P-V after rotation, as illustrated in Fig. 3. It is obvious that coma in these two measurement results is different, which means that there are adjustment errors in wavefront errors gotten by measuring the aspheric surface directly.

In order to give the difference between two figures more clearly, we show the coefficients for Zernike polynomials with $j > 3$ positioned according to their Zernike orders in Fig. 4. Here, the terms of tilt and power are subtracted from the data because they originate completely from an imperfect alignment of the setup. It is obvious that Zernike terms of 6, 7, 13, 14, 22,

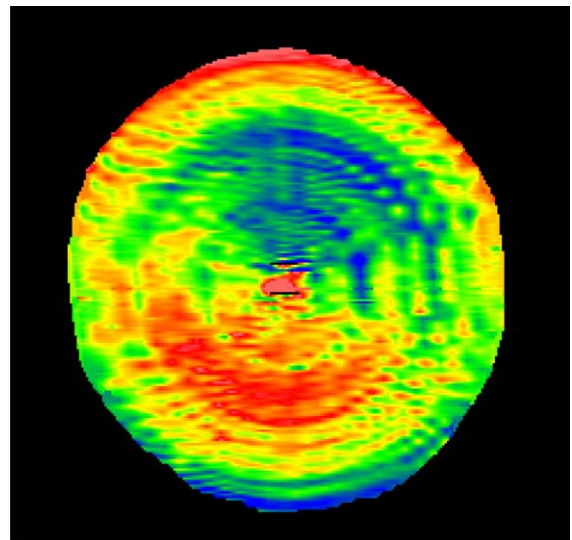


Fig. 5. Phase map with distortion correction.

than before and the phase map fitted with new coefficients of Zernike polynomials is presented in Fig. 5.

4. Summary

In conclusion, we have removed the adjustment errors from measured wavefront when testing aspheric with asymmetric errors in interferometric setups by using Zernike polynomials fitting and measuring it twice. By using a 5-axis Mount with accurate self-centering element holder, a micrometer and a pinhole with 0.3 mm in diameter, we succeeded in keeping almost the same adjustment errors twice. The result obtained by this method is of higher accuracy compared with that produced by direct measurement. It is believed that this method can be used to other interferometric setups with a pinhole at the Fourier plane to remove the adjustment errors from measured wavefront for an aspheric surface with strong asymmetric errors.

The method to adjust the mount we have used works well assuming both an interferometric setup with a small pinhole at the Fourier plane and a

weak aspheric under test. For those setups without pinhole and those aspherics with large deviations from sphere, the adjustment accuracy may greatly decrease. However, this may be compensated when using fiducial marks [9].

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