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Verification and in situ calibration of large-aperture null correctors for convex aspheric mirrors

Shuai Xue, Shanyong Chen *, Ye Tian, Jinfeng Lu, Hao Hu

College of Mechatronic Engineering and Automation, National University of Defense Technology, 47 Yanzheng Street, Changsha, Hunan 410073, China
Hunan Key Laboratory of Ultra-precision Machining Technology, 47 Yanzheng Street, Changsha, Hunan 410073, China

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ABSTRACT

Interferometric test of large convex aspheres with high accuracy is still an urgent problem. Adopting a large-aperture null corrector is usually inevitable, and it is imperative to certify the large-aperture null optics in case incorrect final shape of the aspheric mirror is obtained. Moreover, it is necessary to calibrate and remove errors of the large-aperture null lens and trace errors to surfaces that are easy to obtain high accuracy. For these purpose, this paper presents an in situ calibrated null test method. The large-aperture null corrector for convex aspheric mirror is verified and calibrated by a wisely designed small aperture certifying null whose surfaces are either flat or spherical which are easy to be fabricated, measured and assembled. A redundant test is implemented by a Zygo VeriFire Asphere interferometer for cross test. Compared with existing methods of certificating null correctors which utilize an expensive CGH or a self-aligning aspherical mirror, the presented method finally traces errors of a large-aperture null corrector to small aperture flat and spherical surfaces thus costs are expected to be saved dramatically.

1. Introduction

Large convex aspheric mirrors are widely used in optical systems such as telescopes, etc., and the corresponding surface figure test technique has become a key factor restricting the machining accuracy and efficiency. Among the methods to test convex aspheric mirrors, the Hindle Test [1], Aspheric Test Plate [2,3] and the traditional null test with a large-aperture null optics such as CGH [4,5] and null lens are commonly used. Unfortunately, all these methods require null optics with aperture larger than the test convex aspheric mirror because converging test beam is required. Since the transmitted wavefront quality of the null optics is vital to measurement accuracy, these methods put forward strict requirements on material homogeneity and machining precision of the large-aperture null optics. As is known, the high-precision optical material of a large bulk costs quite a lot and machining a large-aperture lens with good figure quality also costs. Moreover, if there are some defects in materials, or errors occur in manufacturing and alignment of null correctors, the aspheric surface finally acquired will not be correct [6].

To avoid using large-aperture null optics, some methods are proposed. Through the Back Test wisely treats the convex surface as a concave one. However, it only applies to optics of transmitted material, and lightweight structure on the test optics is not allowed. Subaperture stitching technique avoids using a large-aperture null optics by dividing the full aperture into a series of smaller subapertures [7–9]. However, null optics or near null optics is usually required to balance the subaperture aberration [10,11], and both the stitching test process and the data procession are time consuming and susceptible to noises.

Thus testing convex aspheric mirrors still needs a large-aperture null optics in most cases. There are two issues when a large-aperture null optics is utilized, i.e., the certifying and calibration problems. As is known to all, it is necessary to certify (i.e. verify the correctness) the large-aperture null optics in case incorrect final shape of the aspheric mirror is obtained. Moreover, for reducing the impacts of the large-aperture null lens transmitted wavefront error on the convex surface test result and thus saving costs, it is necessary to move out (i.e. calibrate) errors of the large-aperture null lens and trace errors of the large-aperture null lens to surfaces that are easy to obtain high accuracy.

In the field of certifying null correctors, researchers have proposed some useful methods, such as using computer-generated holograms (CGHs) [12–15] or diamond turning aspherical mirrors [16]. In these methods, the certifying elements are required to be

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* Corresponding author.
E-mail address: mesychen@163.com (S. Chen).

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very precise. However, until the present, their manufacturing by most institutes and factories has been immature and expensive compared with traditional optical elements such as flat and spherical lenses. Zhong et al. proposed a novel and effective method [17] which could certify small aperture null correctors simply and economically with just a small aperture spherical lens. However, applying this method for certifying large aperture null optics is no more economical, since a large-aperture spherical lens is required. Moreover, in Refs. [12–17] the researchers have only investigated how to certifying small aperture null correctors for testing primary (concave) mirrors, and certifying large aperture null lens has not been investigated to our knowledge. Furthermore, the certifying result of the null corrector has not been removed from the primary mirror measurement result in Refs. [12–17], in other words, the investigators have just fulfilled the certifying process: verifying the null corrector is correct. However, when the aperture of the null corrector is large, it is necessary to calibrate the null corrector and then remove the errors of the null corrector from the measurement result of the primary mirror. This calibration process will enhance the measurement accuracy of the primary and save costs by utilizing a relatively low accuracy null corrector. Although the aperture of the null corrector for testing primary mirrors needs not to be large, the aperture of null lens for testing secondary mirrors or convex mirrors is large inevitably.

In this manuscript, certifying (verifying the correctness) and calibration (removing out the errors) of the large-aperture null lens for testing convex mirrors are both investigated. For purpose of certifying the large-aperture null lens and tracing errors of the large aperture null correctors for convex aspheric mirrors to flat and spherical surfaces with small aperture, this paper presents an in situ calibrated null test method for convex mirrors which has not been reported to our knowledge. The large-aperture null lens for convex aspheric mirrors is certified and calibrated by a small-aperture certifying null. It must be noted that the calibration is performed in situ wisely, i.e., the test beam travels same path in the large-aperture null lens both in the calibration measurement and the convex mirror measurement, thus transmitted wavefront errors of the large-aperture null lens can be moved out directly from measurement result of the convex mirror and accuracy requirements for the large-aperture null corrector are eased. The measurement uncertainty is finally traced back to the small-aperture certifying null whose surfaces are either flat or spherical which are easy to be fabricated, measured and assembled. A redundant test by a Zygo VeriFire Asphere interferometer is implemented for cross test. Since these two methods are independent, so agreement between the two indicates a high probability that both are correct. It must be noted that, similar with the existing certifying methods [12–17] stated above, we are not trying to fulfill the absolute test of aspherical surface, which is a tough issue and only a quasi-absolute test method has been proposed for aspherical surfaces by utilizing a dual wavefront diffractive optical element (DW-DOE) [18]. Our proposed method is still a relative test, and it requires the small-aperture certifying null to be precise enough. The advantage of the proposed method over the existing certifying methods [12–17] is that the certifying element of our method is easier to be manufactured to a high level accuracy than a CGH or a diamond turning aspherical mirror, and moreover, the flat and spherical surfaces of our certifying null can be calibrated with absolute test techniques such as liquid surface method [19,20], three-flat test and its related methods [21–26], shift-rotation method [27–28], and Pseudo-Shear Interferometry (PSI) method [29].

In this manuscript, the principle of the proposed certification and calibration of large-aperture null correctors is firstly presented. Then experiments are conducted to verify the proposed method.

2. The test principle

2.1. Null lens design and measurement simulations

The asphere tested in this paper is a convex parabolic surface. The material is single crystal silicon. Its clear aperture is 180 mm, and radius of curvature is about 443.735 mm. The root-means-square (RMS) value of figure error is required to be better than $\lambda/20$ ($\lambda = 632.8$ nm). The test convex aspheric mirror is shown in Fig. 1.

A large-aperture interferometer is utilized to test the convex surface with a large-aperture null lens, as shown in Fig. 2(a). The collimated test beam travels through the large-aperture null lens and then hits the convex mirror perpendicularly. The large-aperture null lens is plano-convex with the convex surface facing the interferometer. To ideally balance aberrations of the test surface, the convex surface is optimized by ZEMAX software to be an even asphere with higher order terms defined as below:

$$z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + a_1r^4 + a_2r^6 + a_3 + r^8 + a_4r^{10}, \tag{1}$$

where the curvature at the vertex is $c = 1/(244.2\ \text{mm})$, the conic constant $k = 0$, and coefficients of higher order terms are $a_1 = -6.405 \times 10^{-9}$, $a_2 = -7.269 \times 10^{-14}$, $a_3 = -6.358 \times 10^{-19}$, $a_4 = -1.583 \times 10^{-23}$.

The clear aperture of the null lens is about 214 mm and the central thickness is 59 mm. The RMS value of the residual wavefront aberration simulated by ZEMAX is about 0.001λ ($\lambda = 632.8$ nm) as shown in Fig. 2(b). Note that the residual aberration map is obtained by reading the wavefront map at the image position of the simulation by ZEMAX software. The simulation in ZEMAX is same as Fig. 2(a) only that the interferometer in Fig. 2(a) is replaced by an ideal imaging lens or a paraxial surface, which transform the collimated beam to an ideal point source and vice versa.

Optical design of the aspheric null lens is quite easy and fabrication of the even asphere is also not a problem now, as a number of computer controlled optical surfacing techniques are available such as the magnetorheological finishing [30] and ion beam figuring [31]. The flat surface is first polished to high accuracy, and then the even asphere is figured to produce a high quality transmitted wavefront. Note we do not need to measure the surface error of the convex even asphere directly. The only concern is the transmitted wavefront error, which is a compositive contribution of the

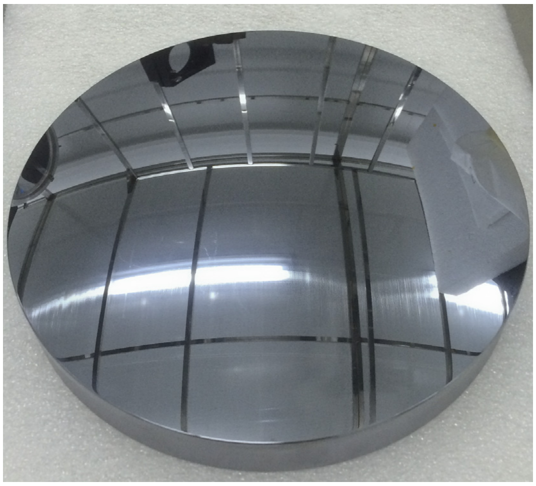

Fig. 1. The test convex aspheric mirror.