Certification of null corrector by a single spherical lens

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In order to certify the accuracy of a null corrector, a method using a single spherical lens is proposed in this paper. An inversed optical path of the infinite conjugated null corrector is introduced, and the aberrations are compensated by using the certifying lens with a reflective inner surface. Initial configurations of the certifying lens are deduced from the aberration characteristics of the null test. A F1.33 ellipsoidal mirror's null corrector is taken for an example. Based on the calculated parameters of the certifying lens, the contribution of the surface's spherical aberration is set as a merit function in the optimization. The root-mean-square wavefront error of the optimized design is 0.0016λ ($\lambda = 632.8$ nm). The method in this paper is simple and low-cost, compared with the existing methods.

OCIS codes: (120.3180) Interferometry; (220.1250) Aspherics; (220.4840) Testing.

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1. Introduction

Because of the progress in optical manufacturing in recent years, aspheric surfaces are widely used in the design of optical instruments [1], especially in large-aperture reflective objectives, such as three-mirror anastigmatic (TMA) and three-mirror Cassegrain (TMC) systems. Manufacture of an aspherical mirror depends on the level of its optical testing. The main methods of testing include the interferometry method, the geometrical ray trace method, and the direct profilometer measuring method [2]. Of all the above, the interferometry method is the most important for high-accuracy testing, which can offer a precise 2D profile of the surface simultaneously while measurement is carried out. With the help of a laser interferometer, testing the aspheric surfaces by null correctors can achieve high accuracy [3–5]. However, if there are some disadvantages in materials, or errors occur in manufacturing and alignment of null correctors, the aspheric surface finally acquired will not be correct [6]. Therefore, certification of null correctors is a very important procedure after its development.

The null correctors produce a large amount of aberrations themselves. So it is very hard to test them directly by traditional image quality testing methods. Researchers in this field have improved some useful methods to certify null correctors, using computer-generated holograms (CGHs) or diamond turning aspherical mirrors [7–11]. It is required that the certifying elements in these methods must be very precise. Until the present, their manufacturing has been immature and expensive, compared with traditional optical elements such as spherical lenses. Certification of a null corrector by a spherical lens is researched in this paper. It is found that, for commonly used infinite conjugated null correctors, a simple spherical lens with a reflective inner surface can accomplish the certification very well, by setting up the optics reasonably.

2. Principle of Null Corrector

Testing of the aspheric surface is performed at the image point in the null test. The image is perfect

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and formed by the optical element under test and the null corrector, which can be composed by lenses, mirrors, or CGHs. The null corrector is used as a component in the aspheric surface's testing. An image with little aberration is achieved using null correctors by introducing a wavefront whose shape corresponds with the aspheric surface under test [12,13].

There are two types of null correctors: the finite conjugated and the infinite conjugated. The infinite conjugated null corrector is much easier to assemble with the laser interferometer, so it is now more popular in optical testing labs. To realize the optical testing of the aspherical mirror, the installation of an infinite conjugated null corrector is shown in Fig. 1. The null corrector has two lenses. One is the corrective lens producing abundant primary spherical aberration. The other is the field lens used for imaging the mirror under test to the corrective lens. The incident plane wavefront is converted by the null corrector to the specific wavefront fitted to the under test aspheric surface's theoretical shape. To realize this, the paraxial focus of the null corrector locates at the same point with the center of the aspheric mirror's vertex curvature. The rays from the null corrector are incident normally on the aspherical mirror, and are self-aligning when the surface under test is ideal. Then a new plane wavefront will be produced and interfered with the reference plane wavefront. Deviation information of the tested surface will be contained in the interferogram.

Based on the principle of null correctors above, obviously, the errors of the null corrector will be brought into the testing wavefront, and influence the result of optical testing. The error of the null corrector comes from the optical materials' optical homogeneity, the surface shapes' accuracy, the glass thicknesses, and the alignment. So, null correctors must be certified before being used to test aspheric surfaces.

3. Certification of Null Corrector

A. Certification Method

In all of the already existent certification methods of null correctors, whether the certifying element is a self-aligning aspherical mirror or a CGH, the directions of incident rays are the same as in the null test system [7–11]. We can call these methods obverse certification. We study in this paper obverse certification of infinite conjugated null correctors. We found that it is very difficult to use a simple element to correct the aberration because the aspheric wavefront of the null corrector is loaded on a beam with a large divergence angle in the obverse certification. Take the self-aligning aspheric mirror for an example; its shape is expressed by a complex function, and its manufacturing must be performed by diamond turning [11].

Is there a simple way to certify null correctors? We are inspired by the wavefront error test of objectives. As is known, there are two types of setups in the objectives' wavefront error test by interferometer. One is using a plane wave to test, as shown in Fig. 2(a). The parallel rays go through the tested objective under test and become an image point, and the rays are reflected by a self-aligning spherical mirror that is assembled after the image point. Then the information of the wavefront error of the objective will be carried by the rays back to the interferometer. This setup is familiar with the existent certification methods of null correctors. The other one is using a spherical wave to test, as shown in Fig. 2(b). The image point of the objective under test is located at the focus of the reference lens. The emergent rays become parallel, and are reflected by a plane mirror. This setup can be called inverse test. It can also test the wavefront error of objectives. Although the inverse test has not been used in certification of null correctors, it is the same as the obverse test. The information of all parameters of null correctors is also contained in the inverse test. So it can take effect in the certification.

For the infinite conjugated null corrector in this paper, inverse certification has an inborn advantage. In the optical path of inverse certification, the divergence angle of the beam is very small in the object space, which means that the spherical aberration may be corrected easier. Based on this thought, we studied the certification of null correctors based on the inverse method.

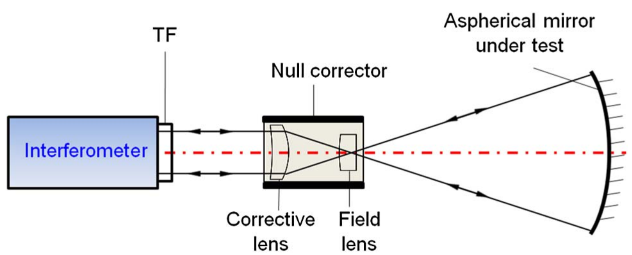

Fig. 1. Installation of infinite conjugated null test.

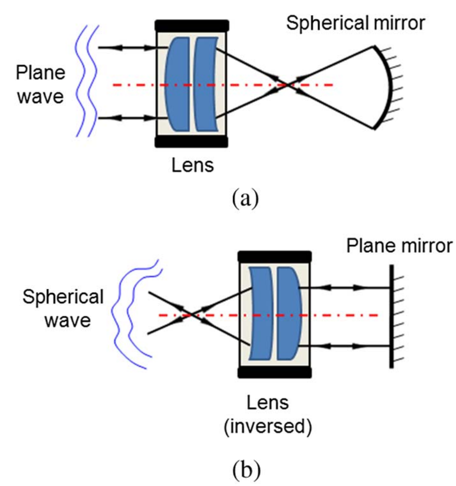

Fig. 2. Installation of lens' wavefront error test. (a) By plane wave (b) By Spherical wave.

B. Calculation of Initial Parameters

The primary spherical aberration of a conic surface is [14]

$$S_I' = S_I + y^4 c^3 K(n' - n). \quad (1)$$

In the null test, rays reflected by the aspheric surface coincide with the surface's normal lines. The primary spherical aberration of the aspheric surface under test can be deduced from Eq. (1) as

$$S_I^a = -2y_a^4 c_a^3 K, \quad (2)$$

where y_a is the paraxial ray's height on the aspherical mirror under test. The value of y_a is equal to the mirror's semiaperture corresponding to the stop of the system. Otherwise, the value of y_a should be acquired by paraxial ray trace. C_a is the vertex curvature of the mirror under test, and K is its conic coefficient.

In the inverse certification, rays emergent from the paraxial focus of the null corrector in the object space become an approximately parallel beam after the null corrector. All information about the null corrector's configuration is contained in this beam. So if this beam can be corrected or self-aligned, certification of the null corrector can be done.

Based on the principle of the null corrector, the primary spherical aberration of the null test system with double passed rays is balanced at the curvature center of the aspheric surface [15], which is

$$2(S_I^c + S_I^f) + S_I^a = 0, \quad (3)$$

where S_I^c is the primary spherical aberration of the corrective lens and S_I^f is of the field lens.

The null corrector is supposed to be corrected by the spherical aberration S_I^1 of a single refractive surface, which is shown as

$$2(S_I^c + S_I^f) + 2S_I^1 = 0. \quad (4)$$

To solve the initial configuration of the certifying lens, the field lens is considered to introduce null aberrations, so

$$S_I^f = 0. \quad (5)$$

From Eqs. (4) and (5), we can get

$$S_I^1 = \frac{1}{2} S_I^a. \quad (6)$$

The primary spherical aberration of a spherical surface is [14]

$$S_I = -[n(u + yc)]^2 y \left(\frac{u'}{n'} - \frac{u}{n} \right). \quad (7)$$

For the infinite conjugated test system, $u = 0$, $n = 1$. So we can get the expression of the refractive surface's radius as

$$r_1 = \sqrt[3]{\frac{(n' - 1)y^4}{n'^2 S_I^1}} = \sqrt[3]{\frac{(1 - n')y^4}{n'^2 y_a^4 c_a^3 K}}, \quad (8)$$

where n' is the refractive index of the certifying lens, and y is the paraxial ray's height on it.

When the aspherical mirror under test is conic concave, trails of calculation will help us know that the value of r_1 is negative. So the front surface of the certifying lens facing the null corrector is concave. A large amount of spherical aberration is produced by this surface, and compensates the spherical aberration of the corrective lens. Therefore, in order to make the residual aberration zero, the other surface of the certifying lens should satisfy the self-aligning condition and contribute zero spherical aberration. This means this surface is aplanatic when it is spherical. The approximately parallel beam from the null corrector is converted to a divergent beam by the front surface of the certifying lens. Obviously, in order to realize the self-aligning reflection, it needs a reflective inner surface whose radius is also negative. Based on the deductions above, the shape of the certifying lens is shown in Fig. 3. It is meniscus shaped.

The radius of the certifying lens' reflective inner surface can be solved by the relationship of optical path length. In Fig. 3, the plane defined by $O'Q_1$ is taken as the wavefront's reference. Based on the self-aligning condition, we can get

$$n'|Q_1Q_2| = |O'P_1| + n'|P_1P_2|. \quad (9)$$

And based on the geometry, we can deduce

$$|O'P_1| = -r_1 - \sqrt{r_1^2 - y^2}. \quad (10)$$

The thickness of certifying lens is set as $|P_1P_2| = d$, so

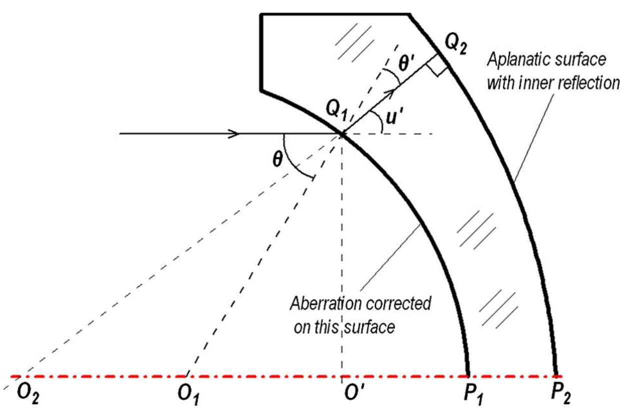

Fig. 3. Shape of the certifying lens.

Table 1. Design Data of Certifying Lens

	Surface	Radius	Thickness	Glass
	Object	Infinity	31.093	
	1	Infinity	20.000	BK7
Null	2	−145.690	122.436	
Corrector	3	61.500	20.012	BK7
	Stop	186.200	81.445	
Certifier	5	−38.877	10.000	BK7
	6	−124.269	—	Mirror

$$|Q_1Q_2| = \frac{-r_1 - \sqrt{r_1^2 - y_1^2} + n'd}{n'}. \quad (11)$$

As shown in Fig. 3, O_1 and O_2 are the spherical centers of the certifying lens' front and reflective inner surfaces. To calculate $|O_2Q_1|$, the equations can be deduced by geometry and Snell's law, as follows:

$$\begin{cases} |O_2Q_1| = \frac{y}{\sin u'} = \frac{y}{\sin(\theta - \theta')} \\ \theta = \arcsin\left(\frac{y}{-r_1}\right) \\ \theta' = \arcsin\left(\frac{\sin\theta}{n}\right) \end{cases}. \quad (12)$$

Then, the radius of the certifying lens' reflective inner surface can be solved by

$$r_2 = -(|O_2Q_1| + |Q_1Q_2|). \quad (13)$$

It is noticeable that, in the calculation of the initial configuration, the stop must be set at the same position with the null test system to make the ray trace data coherent.

C. Design Example

To test the primary mirror of a TMC system in our case, an infinite conjugated null corrector is developed, as in the system setup in Fig. 1. The conic coefficient K of the mirror is −0.988. Its aperture is 600 mm, and the radius of the vertex is −1592 mm. So the F-number of this mirror achieves 1.33. Its relative aperture is larger than many other systems' primary mirrors. The front surface of the null corrector's corrective lens is defined as stop in Fig. 1. Paraxial ray trace is done, and $y_a = 279.9$ mm and $y = 25$ mm are acquired. The materials of the certifying lens and the null corrector lens are all BK7, whose refractive index is 1.515089 at the wavelength 632.8 nm. The thickness d of the certifying lens is set as 10 mm. The initial configuration of the certifying lens is calculated using the equations above. The results show $r_1 = -38.824$ and $r_2 = -130.767$.

The model of the null corrector's inverse certification is set up in ZEMAX optical design software, using the initially configurated parameters. The object point is set at the paraxial focus of the null corrector, and the stop is set at the same position with the null test system. Because the emergent rays of the null corrector are approximately parallel in the inverse optical path, the distance between the

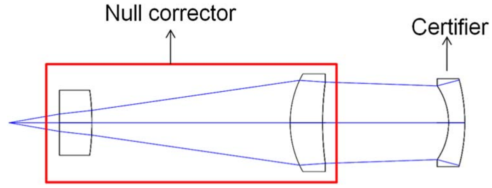

Fig. 4. Layout of certifier design.

certifying lens and the corrective lens will not influence the aberration seriously. So the initial distance can be set arbitrarily in a reasonable range. We let it be 100 mm. The optimization of the certification system is performed in software using merit functions of the wavefront error [16], and the operands of the spherical aberration contribution of both the front and reflective inner surfaces are used. The target of the front surface's spherical aberration contribution is set to compensate the spherical aberration produced by the corrective lens of the null corrector, and the reflective inner surface's spherical aberration contribution is zero. The variables are the distance between the certifying lens and the corrective lens, and the radii of the certifying lens' surfaces. The optimization shows that with a very wide range of distances between the certifying lens and the corrective lens, the merit function can always decrease very fast. And the optimized configuration of the certification system is unique, as shown in Table 1. The null corrector is described by surface 1 to 4, and the certifying lens includes surface 5 to 6.

The layout of the certifier in the system is shown in Fig. 4. It is a very simple lens with ordinary spherical surfaces. The wavefront error of the certification system is shown in Fig. 5, and its RMS value is 0.0016λ ($\lambda = 632.8$ nm), which is at the same level as the null test system design's wavefront error. The certifying lens has only two spherical surfaces. Their accuracy can be manufactured very high by traditional technologies. The material is BK7, whose optical homogeneity can be ensured by high level production. Furthermore, in actual use of the certification system in this paper, the measuring error will be greatly reduced by calibration methods. For example, many measurements with different axial

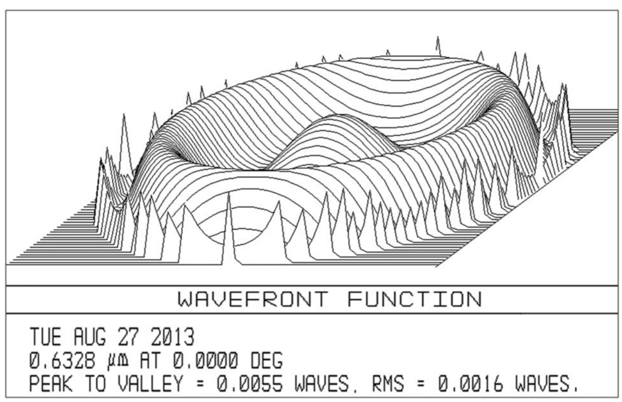

Fig. 5. Wavefront error of certification.

rotations of the certifier are very useful in averaging and deducing the errors. Therefore, the method in this paper can satisfy the highly precise certification need of null correctors in actual applications.

4. Conclusion

Based on the analysis of the null corrector's aberration characteristic, its certification method by a single spherical lens with a reflective inner surface is introduced in this paper. The initial configuration of the certifying lens is accomplished by deducing the equations of primary aberration and the relationship of the optical path. The optimization of the certification system's wavefront error is executed in optical software, and it works well. The example shows that by applying the single spherical lens in our method, the null corrector for an aspherical mirror with large relative aperture can be certified. Compared with the current methods, this method is simple and low-cost. It affords a new method for certification of null correctors for researchers in this field.

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