Convex Aspherical Surface Testing Using Catadioptric Partial Compensating System

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Abstract. Aspheric optical components are the indispensable part of modern optics systems. With the constant development of aspheric optical fabrication technique, the systems with large aperture convex aspheric optical components are widely used in astronomy and space optics. Thus, the measurement of the figure error of the whole convex aspherical surface with high precision comes to be a challenge in the area of optical surface manufacture, and surface testing method is also very important. This paper presents a new partial compensating system by the combination of a refractive lens and a reflective mirror for testing convex aspherical surface. The refractive lens is used to compensate the aberration of the tested convex asphere partially. The reflective mirror is a spherical mirror which is coaxial to the refractive lens and reflecting the lights reflected by the tested convex asphere back to the convex asphere itself. With the long focal length and large aperture system we can realize a lighter and more compact system than the refractive partial compensating system because the spheric reflective mirror is more easily to realize and can bending the light conveniently.

1. Introduction

With the rapid development of astronomy, military and space technology, aspheric optical element has been widely used in optical system to correct aberrations, improve the image quality and simplify the structure of the system, so as to decrease the weight and volume of optical system and decrease the cost[1,2]. Thus, the research of high precision, simple and practical aspheric surface testing technology comes to be an urgent problem to be solved in the application of aspherical surface.

Nowadays, interference measurement is one of the most widely used method in aspheric surface testing with high accuracy[3]. The traditional null compensation testing is a small residual wavefront testing method. The normal aberrations of the aspheric surface are completely compensated by the longitudinal spherical aberration of the null compensator[2]. Thus, null compensator usually requires more lenses[4-5], which is difficult to design and manufacture[6-11]. A method for testing asphere by partial-compensator and digital moiré phase-shifting interferometry was proposed by our research group[12]. Partial compensating method can allow more residual wave aberration, so it can reduce the requirements for optical system design. In addition, the requirement of processing of partial compensator is lower than null compensator and the requirement of system installation is lower than null testing.
However, testing convex aspheric surface is really a trouble in the area of aspheric surface measuring because convex surface can diverge rays, which must be collected and reflected by an optical element, lens or mirror, of sufficient size. This paper presents a new partial compensating system using catadioptric partial-compensator for testing convex aspherical surface. Researches are made on measurement principle, design and optimization method of compensating system. A catadioptric partial-compensator for a specific high-order convex aspheric mirror is designed, and simulation indicates the aberration of this convex asphere is well compensated.

2. Measurement Principle and Methods

2.1. Principle of partial compensating interferometry

A novel interferometric method for measuring the surface figure error of asphere was presented by our research group. It is based on partial compensating principle and digital moiré phase-shifting technique[12].

![Measurement principle](image)

**Figure 1.** Measurement principle.

Figure 1 shows the measurement principle. Aspheric surface testing can be realized by an improved Twyman-Green interferometer. Partial-compensator and the tested asphere are placed into the testing arm of the real interferometer. Real interferogram including the information of the surface error of the tested asphere is detected. In the virtual interferometer, standard reference aspheric surface is produced by digital technology, and thus the fabrication errors of the standard asphere can be avoided. The nominal structure parameters of the partial-compensator are used, and the theoretical interferogram is calculated by ray tracing. The surface error of the tested asphere can be obtained by using digital moiré and phase-shifting interferometry to compare real interferogram with theoretical interferogram.

In this method, partial-compensator is not required to compensate the large wave aberration produced by the aspheric surface under test completely. Some residual wave aberration is allowed to exist, and it is limited by the spatial resolution of CCD for capture the interference fringe.

2.2. Design of catadioptric partial-compensator

As we all know, it is more difficult to test convex aspheric surface than the concave ones, because we need a converging beam produced by a lens or a mirror of sufficient size. This paper presents a new partial compensating system by the combination of a refractive lens and a reflective mirror for testing convex aspherical surface. The compensating optical path displays in Figure 2.
L1 is a refractive lens which is used to compensate the aberration of the tested convex asphere partially. The aperture and curvature radius of L1 is $D'$, $r_1$ and $r_2$. M1 is a spherical reflective mirror which is coaxial to the refractive lens and reflecting the rays reflected by the tested convex asphere back to the convex asphere itself. And the aperture and curvature radius of M1 is $D'$ and $R'$. The vertex of spherical mirror is located near the focal plane of the compensating lens L1. M2 is the convex aspheric surface under test with the vertex curvature radius $R_0$, aperture D and conicoid coefficient k.

As is shown in Figure 2, a collimated beam exiting from the interferometer converged by the refractive lens firstly and then pass through the center hatch of spherical mirror and reflected by aspheric mirror directly into spherical mirror, and then returned to aspheric surface. When the beam is reflected by the aspheric mirror the second time, it transmits back into the interferometer in the original direction.

### 2.2.1 Calculation of initial configuration

The cross section equation of aspheric surface is described as

$$x = \frac{cy^2}{1 + \sqrt{1 - (1+k)c^2y^2}} + Ey^4 + Fy^6 + Gy^8 + Hy^{10}$$

in which, $c$ is the vertex curvature of aspheric surface, $c=1/R_0$, and $R_0$ is the vertex curvature radius. $k$ is the coefficient of conicoid surface, $k=-e^2$, and $e$ is the eccentricity of conicoid curve. E, F, G, H are the coefficient of high-order aspheric surface.

As is shown in Figure 2, the edge ray in the system is incident to the edge of the tested aspheric mirror, and can be reflected by the sphere and transmits back to the interferometer in the original path. In this case, the parameters $D'$ and $R'$ of the spherical mirror can be calculated by ray tracing with some geometrical relationship and Reflection Law.

The parameters $r_1$ and $r_2$ of the refractive lens can be obtained by third-order aberration theory. As is shown in Figure 2, the collimated beam exited from the interferometer refracted by refractive lens for two times, reflected by the spherical mirror for one time and reflected by the aspheric mirror for two times, and then transmitted to the origin eventually. Thus, third-order aberration is balanced. That is to say, in order to achieve the purpose of compensation, spherical aberration generated by the small aperture compensating lens and spherical mirror with large aperture is used to counterbalance the normal aberrations of the aspheric surface. The third-order spherical aberration coefficient of aspheric surface and partial-compensator satisfy the following relations

$$2S_{IL1} + S_{IM1} + 2S_{IM2} = 0$$

in which, $S_{IL1}$, $S_{IM1}$, $S_{IM2}$ represent third-order spherical aberration coefficient of refractive lens, spherical mirror and aspheric mirror under test respectively. The expression of spherical aberration coefficient $S_i$ is$^{1,3}$.
\[ S_I = \Sigma hP + h^4K \]  \hspace{1cm} (3)

in which,

\[ P = \left( \frac{u' - u}{n' - n} \right)^2 \cdot \left( \frac{u' - u}{n' - n} \right) \]  \hspace{1cm} (4)

\[ K = -\frac{e^2}{R_0^2} (n' - n) \]  \hspace{1cm} (5)

\( h \) is the height of the light entering and leaving at each mirror. \( n \) and \( n' \) are the refractive index or reflective index of light before and after the refraction or reflection. \( u \) and \( u' \) are the angle between the ray and optical axis before and after the refraction or reflection.

According to formula (2)~(5) and paraxial optical formula \( n'u' - nu = \frac{h}{r}(n-1) \), the parameters \( r_1 \) and \( r_2 \) of the compensating lens can be solved.

2.2.2 Optimization of partial compensating system

According to the above analysis, the initial configuration of the compensating system are obtained. We put them into Zemax optical design software and set the curvature radius of lens and mirror and the distance between mirrors as the optimization variable. The optimization variables set in Zemax are less than those of null compensating system because the structure of partial-compensator is simpler than that of null-compensator.

The optimization target is the root-mean-square wavefront. Select the appropriate operation to control the edge ray. As the result, the edge ray refracted by refractive lens can be incident to the edge of the tested aspheric mirror. Thus, the full aperture of the aspheric surface can be well detected by controlling the edge ray.

The principle of optimization of Zemax optical design software is Damped Least Square Method. We optimize the partial compensating system in Zemax and the partial compensating system is obtained. The result of optimized design is asked to meet the requirements that the interference fringes can be detected clearly by CCD with 1024 * 1024 pixels, that is to say, the maximum slope of residual wavefront should be less than 0.45\( \lambda \)/pixel\[14\].

3. Simulation Experiment

Taking a convex aspheric mirror as an example, the partial-compensator is designed. This aspheric mirror is a high-order convex aspheric surface with the relative aperture \( D/R_0 \) equal to 1:1.5. Detailed parameters of the high-order aspheric surface are shown in Table 1.

**Table 1. Parameters of the high-order convex aspheric under test**

| D      | R_0    | k     | E        | F        | G         |
|--------|--------|-------|----------|----------|-----------|
| 15.4mm | 25.56mm| -1.01 | 3.2703958e-06 | 7.7205335e-10 | 1.6304727e-13 |

The design and optimization of partial-compensator is performed in the following steps:

1. Set the system parameters

Select wavelength as 532nm. The entrance aperture of the partial compensating system is 80mm, which is the diameter of exit pupil of the interferometer.

2. Calculate the initial configuration of partial-compensator

Set the distance between the spherical mirror and the aspheric mirror as 50mm and the refractive lens is designed with aperture \( D''=90mm \). The parameters of spherical mirror can be obtained from the edge ray in the system by ray-tracing. As a result, the curvature radius \( R' \) is 58.244mm and the aperture \( D' \) is larger than 107.836mm. The curvature radius of refractive lens can be solved according
to the third-order aberration theory mentioned above. As a result, the curvature radius \( r_1 = -1611.514 \text{mm} \) and \( r_2 = -120.901 \text{mm} \).

(3) Design and optimize the partial-compensating system

Put the structural parameters of the partial-compensating system into Zemax. The initial configuration of partial compensating detection system are shown in Table 2.

**Table 2. Initial configuration of partial-compensating system**

| Surf. | type             | Radius/mm | Thickness/mm | Glass | Semi-Diameter/mm | Conic |
|-------|------------------|-----------|--------------|-------|------------------|-------|
| Refractive Lens | -1611.514 | 20        | ZF6          | 45    | 0                |
|       | -120.901        | 134       |              | 45    | 0                |
| Spheric Mirror   | 58.244         | 50        | MIRROR       | 54.651| 0                |
| Even Convex Asphere | 25.56   | MIRROR    | 8.578        | -1.01 |

Set the curvature radius, the thickness, the distance as optimization variables. Set the Default Merit Function and operating function according to Section 2.2.2 in this paper. Optimize the partial compensating system by running the tools of Automatic Optimization. The optimum design of structure parameters, optical path, residual wave aberrations and interferogram of partial compensating system are shown respectively in Table 3, Figure 3-5.

**Table 3. Optimum design of structure parameters partial-compensating system**

| Surf. | type             | Radius/mm | Thickness/mm | Glass | Semi-Diameter/mm | Conic |
|-------|------------------|-----------|--------------|-------|------------------|-------|
| Refractive Lens | Infinity | 8.000     | ZF6          | 45    | 0                |
|       | -209.900        | 274.635   |              | 45    | 0                |
| Spheric Mirror   | 47.75          | 38.067    | MIRROR       | 37    | 0                |
| Even Convex Asphere | 25.56   | MIRROR    | 8.578        | -1.01 |

**Figure 3.** Optical path of partial-compensating system.
4. Conclusions

Based on partial compensation method, a new partial compensating system using catadioptric partial-compensator for testing convex aspheric surface is discussed with a high-order convex asphere in details, whose relative aperture D/R₀ is 1:1.5. The design of catadioptric partial-compensator is the key technology in this method. Assuming the spherical aberration coefficient ΣS₁=0, the initial configuration of partial compensating system is solved based on the third-order aberration theory, and optimized by Zemax optical design software. The result shows that, on the precondition that the interference fringes are detectable, the aberration of convex aspherical surface is well compensated. Compared with null compensating system, the design of catadioptric partial-compensator is much simpler with compact structure, small volume and little optimized parameter.

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