Aberration Analysis for Development of Large- Aperture Reflector by Finite element

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ABSTRACT

The deformation of large- aperture optical mirror is induced by gravity. It is very important to analyze the support structure and format in grounding and testing. By finite element software, a Φ620mm mirror is created and its theoretical analysis about three comparative testing programs of vertical support is proposed. Zernike polynomials are used to fit optical surface and separate corresponding aberrations. By reducing the aberrations with great impact on mirror, at the same time, RMS excel 0.025λ (λ=632.8nm) has been achieved. Experiments of three kinds of support verify that the entirely bound by strip is the best way in all supports. It affords a more scientific and rational support to large-diameter optical mirror reflection. Through research and analysis of support on large-diameter mirror by finite element, it provides a theory of design and guidance for the development and test of reflection mirror in future.

Keywords Large- aperture optical reflector; Support; Finite element；Zernike polynomial; Aberration

1. INTRODUCTION

Large- aperture optical system will improve equipment and increase the ability to distinguish signal energy. With the development of science and technology and the demand for scientific exploration, application of large-diameter optical components is more and more extensive. Its areas are related to large-scale ground and space telescopes, space remote sensing equipment, etc. In astronomical research, large-aperture optical components, in particular, the aperture is greater than 500 mm, the application of reflector is much normal. For large-diameter telescope, processing and testing are indispensable pivotal technologies in development of high-quality large-diameter mirror. In addition, some special areas of application, mirror's micro-structure of the wave-front, there are special requirements in space wavelengths which is in wave-front error of sub-millimeter and millimeter-wave. So testing the quality of the surface shape is very important in manufacturing process. However, the application of mirror reflection is more common. Processing and testing are to meet demand for large-diameter optical system in testing. The surface is deformed greatly by its gravity. Therefore, it needs matched supports. If the form of support is inappropriate, it causes the surface quality of reflector deteriorated, and leads to a serious decline in image quality. Thus it can not meet the optical system to better image quality requirements. This paper aims at Φ620 mm spherical primary mirror, putting forward comparative analysis with three kinds of methods of vertical testing. Zernike polynomial is adopted to fit surface and separate various aberrations. It carries out verification by experiments that improved support quality and reliability of large-diameter optical reflection in different states, and proposes a better way of support to correct various aberrations.

With a round plate theory to analyze the mirror self-respect deformation, the bending of the mirror is w.

$$w = \frac{qa^4}{k}\overline{w} = \frac{h\rho(\frac{D}{2})^4}{\frac{Eh^3}{12(1-\mu^2)}}\overline{w} \cong 0.703\frac{\rho}{E}\frac{D}{h^2}\overline{w} \tag{1}$$

w : the actual deformation of a point on circle board ; $\overline{w}$: "planning" deformation of the same point(which depends on the support of mirror and has nothing to do with the size of the mirror) ; ρ、μ、E:constant proportion ,Poisson's ratio and

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Young's modulus of materials; D、a、h:Geometry diameter, thickness and radius; q:Load density q=h*ρ; K:plate stiffness:

$$k = \frac{Eh^3}{12(1-\mu^2)} = 0.0889Eh^3$$

This shows that $\overline{w}$ is optimization of the areas, it is important to select a reasonable way of support for the surface of the mirror.

2 Creating a model by Finite element and fitting the surface of reflector by Zernike polynomial

The basic principles of the static deformation by Finite element analysis is: meshing the structure will be a limited number of "units" and nodes; displacement fields of the structure will show the interpolation function of nodes, thereby the deformation and stress (or internal forces) fields become interpolation function of nodes' displacement. And according to the "virtual work principle", it can establish the balance equation of the structure and obtain node displacement.

Large- Aperture optical mirror is deformed greatly induced by gravity. The deformation of surface is usually expressed as RMS or peak values which are figured axial deviation between many points and a best-fitting surface in terms of the reflector, the ideal of reflecting surface is the best-fitting surface.

2.1 Creating a model

Creating a entity model of Φ620mm-spherical primary mirror, y-axis is the optical axis direction, and coordinates is the center of bottom. Various parameters are shown as Table1:

Table1: Parameters of the reflector

Material(K4 glass)		Physical prosperities	
Young's modulus E/(MPa)	7.1e4	Diameter D1/mm D2/mm	620 65
Poisson's ratio μ	0.21	Thickness t/mm	110
Material density ρ/ (kg/m3)	2500	Radius of curvature/mm	760

With Solid45 of element meshing the structure is shown in Figure1.The number of nodes on surface is 2304. Calculating the center coordinates of mass is (0, 40.713, 0), the quality is 57.3481kg.

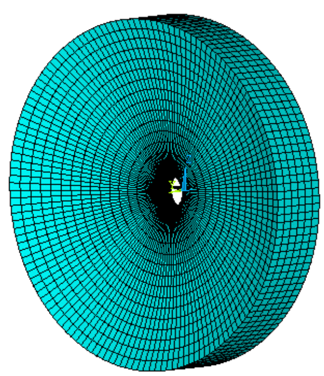

Fig.1: Grid of Finite element

2.2 Zernike polynomial

Fitting the surface is using Zernike polynomial. Because it is mutual orthogonal on the defined unit circle and it has a certain relationship with primary aberration. It is easy to establish a link between Seidel aberration function and them in

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optical design. It provides an effective method to deal with various aberration coefficients and optimize system performance. Polynomials can be expressed as $r^n \cos m\theta$ and $r^n \sin m\theta$ that is in the form of coordinates defined with radius and azimuth. Any k-rank function can be expressed with a linear combination of Zernike round polynomial:

$$w(r,\theta) = \sum_{n=0}^{k} \sum_{m}^{n} A_{nm} R_n^{n-2m} \begin{Bmatrix} \sin \\ \cos \end{Bmatrix} (n-2m)\theta \tag{2}$$

Where $R_n^{n-2m}(r) = \sum_{s=0}^{m} (-1)^s \frac{(n-s)!}{s!(m-s)!(n-m-s)!} r^{n-2s}$

As a general optical system will not have great senior aberration. It is adequate accuracy to describe the aberration with 7-rank. This article is taken 36 Zernike polynomials to fit the surface.

$$w[i] = \overbrace{qztw[0]\times 1 + qztw[1]\times x[i] + qztw[2]\times y[i] + \ldots\ldots}^{36} \tag{3}$$

(W [i]: transformation of node "i" in the optical axis (z-direction) which is on the surface of finite element model; qztw [0]: piston coefficient; qztw [1]: x-direction tilt coefficient;
qztw [2]: y-direction tilt coefficient; x [i], y [i]: x, y- coordinates of node "i" after the normalization)
In order to deal with some separate aberration conveniently, it will remove the aberration for data processing in the proceedings.

$$w_0[i] = w[i] - P \tag{4}$$

(P is a particular aberration polynomial such as Spherical, astigmatism, coma, tilt, power and so on ; $w_0[i]$ is the transformation of node "i" in the optical axis (z direction) after eliminating an aberration)

3 Comparative Analysis for testing of vertical program and the corresponding aberration results

3.1 Options of support

The support of Large-diameter mirror plays a decisive role on stress and deformation, choosing a reasonable support for optical properties of mirror is of critical importance. There are many common vertical supports such as a strip support, point support, in the hole and surrounding side support, etc. At the same time the comprehensive support such as safety, convenience and economy are taken into account.
In general, uniform and more supports make mirror less deformable, but considering structure and cost, less supports is the hope that is a problem of optimal design. Of course, an important principle role of lateral support is the location of support (or its efforts) focused on center of gravity plane in the mirror. Otherwise they will be uneven and give additional support forces at the bottom.

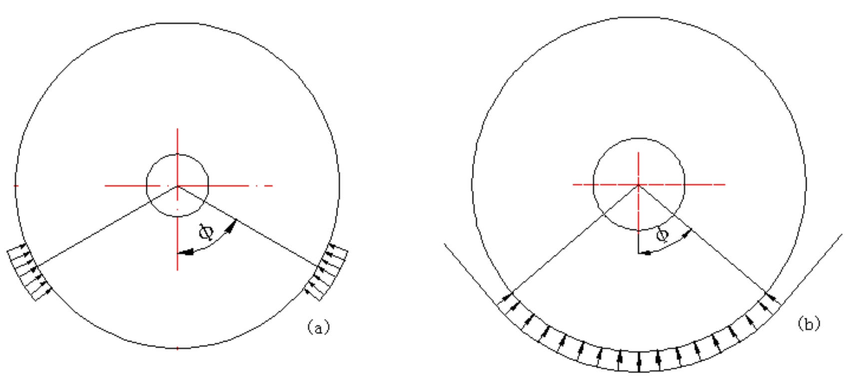

Fig.2: (a) 2-point support (b) strip support

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In Fig.2, the point support is a small arc whose corresponding center angle is about 180^0. The centre angle of two points is 2φ. From the information in the past, $2\varphi= 120^0$ is the best location in 2-point support. In this paper, take the angle as analysis. There is information shown that $2\varphi=180^0$ is the best location in strip support. In the actual testing, it is likely that it will change the contact areas with the mirror when the strip goes forward or backward movement. This article is about the comparative analysis of full contact($y\in[0,110]$) and local contact($y\in[20,110]$). The corresponding deformations of displacement in optical axis direction are shown as Fig.3, Fig.4, Fig.5. And the table 2 shows RMS value in there kinds of supports by finite element. (for color image please see online version of paper)

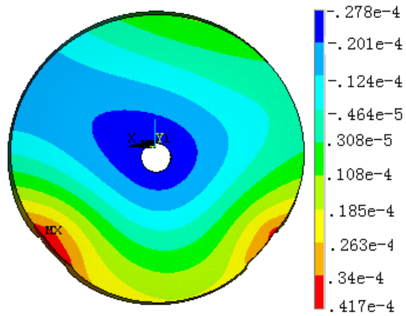

Fig.3: Deformation of displacement in optical axis direction of 2-point support (Units: mm)

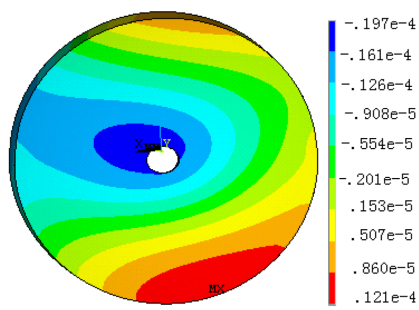

Fig.4: Deformation of displacement in optical axis direction of full contact strip support (Units: mm)

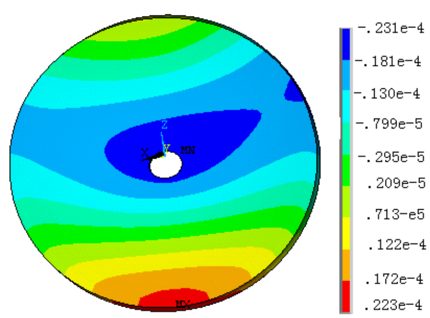

Fig.5: Deformation of displacement in optical axis direction of local contact strip support (Units: mm)

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Table 2: RMS value under these ways of supports

Ways of support	RMS(nm)
2-point support	16.53203568
Full contact strip	10.84715045
local contact strip	14.16814815

3.2 Aberration analysis

To fit the deformation of the spherical reflector with Zernike polynomial, separate the aberrations which are induced by deformation and have a data processing of eliminating tilt, power, astigmatism and coma. The results are shown in Table 3.We can see that the value of power is the largest, but the impact of coma is the smallest for the surface in these ways of supports. Although the 2-point support which compared with the other two ways has a great role of reducing astigmatism, its RMS value is larger than others'. The structure of full contact strip support is relatively simple, but the horizontal squeezing pressure is larger which makes astigmatism become larger than before. Overall, the full contact strip support is the best way in these supports.

Table3: Dealing with aberration (Units: nm)

Load conditions	Errors	After fitting	eliminating coma	Eliminating tilt	Eliminating astigmatism	Eliminating Spherical	Eliminating power
2-point-	PV	64.612878	63.620550	57.787769	66.764734	64.898327	56.883914
support	RMS	14.669061	14.678111	13.144108	14.262839	14.072161	8.942536
Full contact-	PV	30.518101	33.052152	31.809594	30.561988	31.690269	29.864846
strip	RMS	8.193799	8.090198	6.962733	7.570204	7.761245	5.803380
local contact	PV	40.812098	42.738739	40.283238	31.030049	41.749726	39.766818
-strip	RMS	10.093657	10.014864	8.710620	8.545098	9.686225	7.809306

4 EXPERIMENTS

In this paper, there is a real testing on the completed Φ620 mm spherical primary mirror. Collect the actual surface data collection with WYKO interferometer. The data includes: the error in the processing, the error from support, the impact of air currents, temperature effects, man-made factors in testing and so on. The accuracy of the actual the mirror is based on customer requirements. The experiment gets a good surface figure with the mean of full contacts strip support. The mirror is defined 4 different directions such as 1-up, 2-up, 3-up, 4-up. The RMS value is requested at the time. They are shown as Fig.6, Fig.7, Fig.8, Fig.9 those are tested in 4 different directions (for color images see online version of paper)

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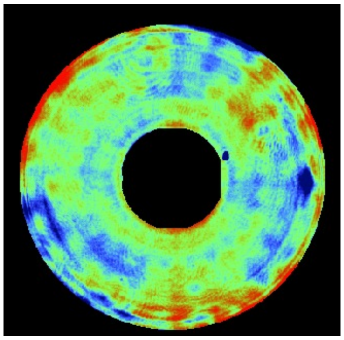

Fig.6: Surface figure (1-up)

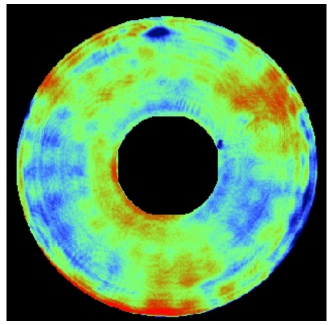

Fig.7: Surface figure (2-up)

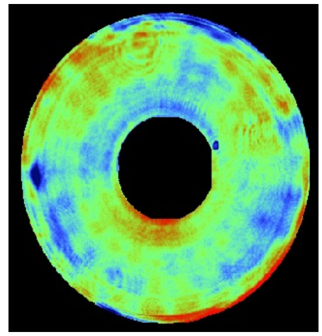

Fig.8: Surface figure (3-up)

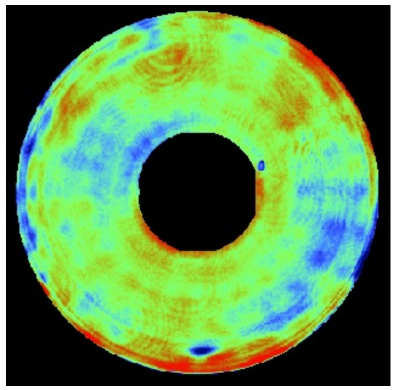

Fig.9: Surface figure (4-up)

Table4:RMS in 4 different directions

direction	1-up	2-up	3-up	4-up
RMS(nm)	11.3904	12.656	13.2888	13.2888

5 CONCLUSION

In this paper, there is a theoretical simulation on supports of large-diameter reflection in developing. It provides a good theoretical basis for the practical application. In the vertical support, through the integration of theory and practice, finding the best way in reducing the impact of the corresponding aberration in testing is very necessary. The way of support is a variety in testing, there is a variety of factors having an affect on actual development and testing. We have to try to minimize the impacts which are objective or subjective factors on the mirror. It is need to be improved in the facilities and testing methods. According to this paper, with the technical mastery of the finite element analysis and calculation we have had a testing on the SIC φ616 mm aspheric mirror for the vertical support. The good test results which have been verified. Φ920 mm plane mirror was also made finite element analysis and calculations of the vertical support. Its effect will to be verified in the latter part of the application.

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