Strategies of primary mirror segment fabrication for CFGT

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ABSTRACT

An extremely large telescope named Chinese Future Giant Telescope (CFGT) has been presented. The primary mirror of CFGT is a 30-meter diameter hyperboloid with a focal ratio F/1.2 and it consists of over one thousand of sector-shaped segments with the size about 1.1-meter in diagonal. Based on the optical design concept and the experience of existing large segmented primary mirror, we explore the segment fabrication and testing issues in this paper. The relationship between external contour, the size and the asphericity of sub-mirror is studied. Two potential segment fabrication approaches for mass-production-scale are discussed. One is the optical replication. The other is stressed-mirror polishing. Both of two processes are tightly combined with several key techniques and devices, the ion-beam figuring, large annular polisher, and the stressed lap. Some preliminary concepts for testing of 1-meter class convex/concave off-axis aspheric surface are discussed.

Keywords: Segmented primary mirror, off-axis aspheric optics, optical fabrication and testing

1. INTRODUCTION

The research works on the Extremely Large Telescope in China have been started for several years. Su etc. presented several optical systems for 30-100m optical and infrared telescope in SPIE's conference in 2000^[1]. After that, they detailed the proposal and put forward a 30-m telescope which is made as a candidate for Chinese Future Giant Telescope (CFGT). CFGT includes Nasmyth, coude and wide field of view optical systems. In the proposed configurations, the parameters of the primary are somewhat different when the optical system transform from Nasmyth system to coude's and wide field of view one. They keep the surface figure of all segments and manage to re-adjust a little the locations for them and get the required surface shape for whole segmented primary ^[2]. One of characteristics of CFGT is its segment scheme that is different from other large telescope projects, in use or in construction. The segments of CFGT are sector-shaped while others are hexagon-shaped. This change is mainly based on the consideration for optical manufacturing. Because there are thousand of large aspheric optics needed to be fabricated, the rapid, mass-production-suited processing approach are strongly required. The designer of CFGT noticed that and segmented the primary into sector-shaped sub-mirrors for such arrangement seems to adapt to using the method of optical replication. In this paper, we will discuss some technical issues of optical replication for manufacturing the CFGT primary.

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2. THE PARAMETERS OF CFGT PRIMARY AND THE SEGMENTS

The primary of CFGT is a 30-meter diameter hyperboloid with a 2.8-meter central hole. The surface radius of curvature at vertex is 72-meter long that is the focal ratio is F/1.2.

The primary is divided evenly to 17 rings from central hole to the outer edge. Each ring is 0.8m along radial direction and then divided evenly into small sectors along the circumference. It is noticed that for those sub-mirrors located in the same ring have the same surface shape. There are only 17 different shapes in all sub-mirrors. In this situation, the size of each kind of segment is about 1.2-meters in the largest dimension. The arrangement and the geometric size of segments are shown respectively in Fig. 1 and Table 1. The total number of segments is 1020. If we prepare a spare for each kind of sub-mirror, the total number will be 1037.

Segment	Inner radii(m)	Outer radii (m)	Sum of segments	Segment size* (mm)
1 st ring	1.4	2.2	12	1210
2 nd ring	2.2	3.0	18	1198
3 rd ring	3.0	3.8	24	1190
4 th ring	3.8	4.6	30	1185
5 th ring	4.6	5.4	36	1181
6 th ring	5.4	6.2	42	1178
7 th ring	6.2	7.0	48	1176
8 th ring	7.0	7.8	54	1174
9 th ring	7.8	8.6	60	1173
10 th ring	8.6	9.4	66	1171
11 th ring	9.4	10.2	72	1170
12 th ring	10.2	11.0	78	1169
13 th ring	11.0	11.8	84	1169
14 th ring	11.8	12.6	90	1168
15 th ring	12.6	13.4	96	1167
16 th ring	13.4	14.2	102	1167
17 th ring	14.2	15.0	108	1167

Table 1 Radial segmentation geometry of CFGT

*Cast in the plane perpendicular to the optical axis.

Refer to the similar 30-meter telescope $\text{projects}^{[3-4]}$, for example, GSMT(Φ 30-m, F/1 primary)and CELT(Φ 30-m, f/1.5 primary), the primary was segmented into hexagon-shaped sub-mirrors. The diagonal of segment is 1.33-meter and 1-meter respectively. As for the segmentation of CFGT primary, if the hexagonal segment is chosen and the diagonal size is 1.1-meter(same as LAMOST^[5]), the scheme will be shown in Fig.2. The sum of segments is 888 including 148 kinds. The light-collecting area is 697.9 m², equivalent to 29.8-meters in diameter. And the largest size is 31.44 meters. Adding

the spares, the total segment will be 1036.

When the primary consists of sector-shaped sub-mirror, the amount of types is only depended on the segmentation in the radial direction. If we change the segment size along the circumference and keep the radial size of segment. The total number is changed but the kinds of segment are kept the same. For example, we can re-arrange the above-mentioned CFGT primary in sector-shaped. Keeping the 17 rings and adding 6 pieces for each ring, the total number of segment will increase 102, and the size of segment will decrease from 1.2-metre to 1.13-meter. On the other hand, if we re-arrange the above-mentioned CFGT primary in hexagon-shaped segments, when the diagonal decrease from 1.2-metre to 1.13-meter, 96 pieces in the total number of segment including 16 kinds will increase. Comparing these two cases, the former has fewer types of segment and has fewer changes in kind while the segments size changed. It seems easy to administrate during the productive procedure.



Fig.1 Layout of CFGT primary

Fig.2 Primary with 1.1m hexagonal segment

3. THE ASPHERICITY OF SUB-MIRROR

For the sector-shaped segmentation, basically, the outmost one deviates most from a sphere. The deviation for each kind of segment can be numerically calculated. Based on the geometric feature of sector-shaped mirror, some special points on the mirror surface are chosen to restrict the parameters of the best-fitting sphere. These points lie on: (i) 2 points in the edge of meridian section (Fig. 3a); (ii) 1 point in the edge of meridian section and 2 points at the corner (Fig. 3b, Fig.3c); (iii) 4 points at the corner (Fig. 3d).



Fig.3 The restrict condition for the best-fitting sphere

Proc. of SPIE Vol. 5494 331

The maximal asphericities under the different restrict conditions are calculated. It shows that the case (iii) gives minimal deviations in both the PTV value and the RMS value. The results of case (iii) are shown in Fig. 4. The aspheric contours of 1^{st} ring and 17^{th} ring segment are shown in Fig. 5. As the figure showed, the astigmatism dominated the surfaces. The asphericity is about 50µ in maximum.



Fig. 4 The asphericity of the 17 different types of sub-mirrors



Fig. 5 The contour of the asphericity

4. SUB-MIRROR FABRICATION

When the amount of sub-mirror increases to hundred and thousand, conventional method of astronomical mirror fabrication will meet unconquerable obstacles. By now there are two ways to fabricate aspherical sub-mirrors on a large scale: one is stressed mirror figuring technique, the other is optical replication technique. The former has successfully applied in KECK telescope construction and has been proven competent to this kind of task. The application of latter can

be found in ESO's VLT project^[6]. It had managed to build the secondary mirror (about 1m in diameter). Though the replication mirror did not come to final installation, it is really a technique with both great efficiency and low cost to fabricate segmented sub-mirrors.

4.1 Stressed Mirror Figuring Technique

Stressed mirror figuring was developed for fabricating KECK Telescope's segmented primary mirror. One virtue of this new technique that should be mentioned is it is well suited to polish off-axis aspherical mirror. When SMF is scheduled to apply, the first step is to make the sub-mirror into a circular disk shape. Then we add forces and moments around the edge to induce a surface shape with astigmatism and coma of the opposite sign to that desired for final surface. While the blank is held in this deformed state, a spherical surface is ground and figured. After figuring, the forces and moments are removed and the mirror elastically deformed into the desired surface shape. Finally cut the mirror into desired shape and use ion beam figuring to correct errors introduced by cutting.

Another possibility is to use the stressed polishing directly with the sector-shaped segment mirror to avoid the warping of the mirror surface after cutting process. It should be an advantage by the stressed polishing technique for the sector shaped segments because of its aspherical surface with two principal curvatures distributed symmetrically with the four outer edges, that is to say for applying the bending moment should not be difficult on the sector–shaped segment. Also the fine polishing could be done by ion beam figuring if it is required.

In KECK telescope, the diagonal of sub-mirrors is 1.8m and focal ratio of primary mirror is F/1.75. If we select the dimension of CFGT's sub-mirror with 1.1m and focus our attention to the marginal sub-mirror of CELT and KECK. Then we can compute the Zernike polynomial coefficients and list them in table 2 for contrast. Results are very clear and we conclude as followings: (a) the asphericity of sub-mirror in CFGT is dominated by astigmatism. (b) C_{22} which represents the astigmatism in CFGT is about the half of that in KECK. (c) In comparison with astigmatism, CFGT's coma aberration is small and C_{31} occupies only 10 percent of the corresponding part in KECK. According to our experience, astigmatism is easier to correct through applying moments around the edge than aberrations.

	KECK	CELT	CFGT
Primary diameter (m)	10	30	30
Primary focal ratio (F)	1.75	1.5	1.2
Sub-mirror dimension (m)	1.8	1	1.1
C ₂₂ (microns)	-100	-19	-45.4
C ₃₁ (microns)	-13	-0.4	-1.04

Table 2 The coefficients for the outmost segment of KECK, CELT and CFGT

Fig.6 shows the relationship between Zernike polynomial coefficients and the off-axis distance for CFGT and CELT. In these two telescopes the diameters of primary mirror are the same, yet they differ in such aspects as the dimension of sub-mirror and focal ratio. The sub-mirror's dimension in CFGT is 1.1 times than that of CELT and focal ratio 1.25 times (1.375 times for sub-mirror) than CELT. So the Zernike coefficients of CFGT are approximately double or triple of those in CELT.



Fig.6 The Zernike coefficients versus off-axis distance for CELT and CFGT

To implement stressed mirror figuring there are two kinds of auxiliary equipment. One of them is annular polish machine. It can fabricate mirrors on a large scale with great efficiency. Although used for manufacture flat mirrors generally, it is suited for figure mirrors of large telescope. Because the curvature radius of astronomical mirror is very large, so during the process of figuring sub-mirror, the best-fitting sphere is very close to flat surface. Large annular polish machine can figure several mirrors at one time. In order to polish thousand of mirrors, we plan to equip several machines used for grinding and polishing respectively. In NIAOT, we have established a 3.6m diameter annular polish machine and it can polish three sub-mirrors (all 1.1m in diameter) simultaneously as shown in Fig.7. Up to present we have laid solid foundation to carry out stressed mirror figuring technique on 1-m diameter mirror using our annular polishing machine. We also expect to build annular polishing machine with larger diameter to increase the figuring efficiency in near future, such as 5m diameter annular polishing machine which will be able to figure 5 mirrors (all 1m in diameter) at one time illustrated in Fig.8. The second equipment we need is ion beam figuring machine. It excels in correcting high frequency errors on the surface figured at last stage. After cutting the mirror from the circular shape to the desired shape, the residual high frequency error should be modified by ion beam figuring technique, or the ion beam polishing could be used for the fine polishing in the last process for the mirror surface.



Fig. 7 3.6 m annular polishing machine



Fig. 8 Polishing 5 segments together on a 5-m annular polisher

4.2 Optical replication

A replicated optical surface is obtained by molding a thin (about 0.1-mm) layer of resin on to the surface of a rigid substrate. The latter must be shaped down to a surface accuracy which is one or two orders of magnitude lower than the final specification to be met. The process route of optical replication is shown in Figure 9. In CFGT primary, there are only 17 different shapes for all sub-mirrors. That is, only 17 molds for all replicas are needed.



Fig. 9 Layout of the replication process

Some preliminary experiments on replication have been done. The experiments showed that mirror replication technique is able to produce mirror with expected accuracy. About 0.05λ rms surface accuracy is reached on several Φ 200-mm substrates^[7]. An interferometric fringe pattern of a Φ 200-mm spherical replica is shown in Fig. 10. In comparison with classical polishing techniques, it is obvious that the mirror replication offers the

financial benefits for mass-production.

The sub-mirrors of CFGT primary are larger in dimensions and higher in surface accuracy. The issues on practicability and feasibility need to be studied in next step. Besides replication itself, some relative technical issues are listed below:

The fabrication of off-axis convex masters: There are two approaches to be employed. The one is to use first the stressed-mirror polishing then ion beam figuring. The question is that the thickness of the master should be thinner than conventional otherwise the blank is difficult to bend. For such large optics, the thinner thickness means the master tends to deform during replication. The other one is stressed lap polishing developed by Steward Observatory Mirror Lab^[8]. In NIAOT, the technique has been studied for polishing a 0.9-m axis-symmetric paraboloid. The mathematic model of the lap is been studied for polishing the non-symmetric aspherics.



Fig.10 Interferogram of a spherical replica

The fabrication of substrates: as mentioned before, the maximal asphericity is about 50μ and the thickness of optical resin is only about 100μ . In order to obtain the higher surface accuracy, the substrate of sub-mirror should be ground down to a surface accuracy, say several microns. For these reasons, large annular polishing machine and stressed-lap both for rapid grinding are needed to be equipped.

4.3. Ion beam figuring

As above-mentioned, the ion beam figuring played an important role during the mass-productive process of large optics. In order to obtain the high accuracy, it is necessary to using the ion beam figuring device whether in stressed mirror

polishing or in the optical replication process.

The principle of ion beam figuring is to bombard the mirror surface with low energy ions generated by ion source. By removing substrate material with ion beam sputtering in a carefully controlled manner, we can acquire satisfied surface shape. The whole process is carried in a vacuum chamber.

There is no difference between IBF technique and traditional Computer Controlled Polish (CCP) in mathematical theory. Under this model, we assume that E(x, y) represents the error distribution on the mirror surface. F(x, y) represents the material removal profile of the ion beam. And T(x, y) is the time the center of ion beam dwelling on each point (x, y). The relationship of E(x, y), F(x, y) and T(x, y) satisfies the following formula.

E(x, y) = F(x, y) * T(x, y)

If we know E(x, y) and F(x, y) we can calculate T(x, y) using deconvolution program. After that let the ion beam scan the mirror surface according to the calculated control strategy.

Some experiments have been done on existing vacuum equipment to test the removing effect of substrate material under ion beam bombardment. The result can be illustrated clearly by Fig.11 on which the bombardment effect is very obvious. All data on Fig.11 is come from WYKO interferometer, thus we can get the ion beam removal profile F(x, y) immediately from this picture.





We have ordered a special equipment for ion beam figuring. Two different ion beam source can be installed in it. One is larger in diameter and the other smaller. According the reference ^[9-11], ion beam with small diameter can get higher figuring precision than the larger one but lower efficiency. So combined with these two different ion source we can realize both rough and precision machining.

Two modes existed for how to scan the mirror: one is polar coordinates or (ρ, θ) mode, the other is canonical

coordinates or (x, y) mode. The new equipment can realize both. Furthermore it can emulate whole process of

figuring easily.

We have developed computer controlled software for ion beam figuring technique and Fig.12 is the interface of this software.



Fig.12 The interface of computer controlled software for IBF.

4.4 The blank of segment

The zero-expansion glass ceramic will be served as segment blank in principle. The replicating masters are the same. These materials include SCHOTT Zerodur, JSC LZOS Astro-Sitall and XINHU VO₂. It is noticed that the excellent characteristics of CFRP. Because of small density, higher Specific Stiffness (Young's Modulus/density) and Thermal diffusivity (CTE/Thermal Conductivity), lower Steady state distortion (CTE/Thermal Conductivity) and Transient distortion (CTE/Thermal diffusivity), maybe the material will become the best candidate especially in replication.

5. SEGMENT TESTING

According to the process route of the replication, the testing procedure will be performed in following steps:

Grinding the substrate of segment.

Grinding the convex master.

Polishing the convex master.

The sub-mirror after replication.

During the grinding step, the profilometer will be served as main instruments. The best type of profilometer is that to be using array of linear variable differential transformers (LVDTs) because the test is performed on off-axis aspheric surface. A similar testing setup with 4×4 LVDT array has been built in NIAOT. It is used to test a 300×300 aspheric surface. This configuration is similar to that used by Steward Observatory Mirror Lab to calibrate their stressed lap. In CFGT metrology, the profilemeter with the capability of 1-meter in dimension and up to hundred microns in measurement range is required.

The final figure of the CFGT will be achieved by replication. The surface accuracy heavily depends on the accuracy of convex master. In principle, the 1-meter class holographic test plate^[12] can be used in the CFGT segment measuring, both in the finished segment and in the convex master, only that the aspheric optics under test before are axis-symmetrical.

Based on the geometry of the primary of CFGT, it is a hyperboloid and the fuci are lie on the 35.992-meters and about 166-kilometers away from its vertex respectively. The primary can be tested just like the paraloiod when a Φ 200-mm compensate lens is put near by its closer focus. A segment testing configuration using the compensator and a 1-m class return flat is shown in Fig.13. In the configuration, several adjacent segments can be measured together if a larger flat mirror is used.



Fig.13 Testing segments with a compensator and a 1-m class return flat

Using a standard spherical mirror and a large lens, the convex master can be measured. It is shown in Fig.14. The curvature center of the spherical mirror is put on the closer focus of the convex surface under test, which is conjugated to its further focus.

Putting a light source on the focus of a large lens, say 1.1-meter in diameter, the conjugated image distance is in infinity. While the light source goes away from the focus a little, a required image distance, say 166-km, can be reached. In this way, the light source can be conjugated with the fuci of the convex surface under test. For example, if the focal length of the lens is 8000-mm, the defocus will be 0.38mm.

In order to avoid the obstruction in the optical path, the distance between convex master and the spherical mirror should be large enough when the off-axis distance becomes small. But the large surface gap makes large standard mirror size. For example, in order to test 1st ring master without obstruction, the surface gap should be about 40-meter and the standard mirror should be 2.4-meter in diameter.

Considering these situations, the distance between two surfaces is limited within 10-metres. 12 types master can be tested with 2 standard spherical mirrors. The convex masters from 6^{th} to 11^{th} ring are tested with a Φ 1.5-meter sphere at 10-meter surface gap. The one from 12^{th} to 17^{th} ring are tested with a Φ 1.2-meter sphere at 5-meter surface gap.



Fig. 14 Testing the convex master with a standard mirror and a big lens

Another scheme applied to the testing for the masters from 1^{st} ring to 5^{th} ring is shown in Fig. 15. Two small lenses are used. One lens is introduced a cylinder surface. It is used for compensating the astigmatism. Another lens is tilted a little for eliminating the coma. The design shows less residual wave-front errors. The results are less than 0.035λ (PTV) at λ =632.8-nm for all the masters from 1^{st} to 5^{th} ring.



Fig. 15 Testing the convex master with a big lens and a set of small lens

6. SUMMARY

The CFGT brings us a great challenge in the optical manufacturing and testing. After preliminary explore on the relative techniques, general strategy is clarified. These techniques will lead our research activities in the future.

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