Active Control of the Chinese Giant Solar Telescope

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ABSTRACT

The Chinese Giant Solar Telescope (CGST) is the next generation solar telescope of China with diameter of 8 meter. The unique feature of CGST is that its primary is a ring, which facilitates the polarization detection and thermal control. In its present design and development phase, two primary mirror patterns are considered. For one thing, the primary mirror is expected to construct with mosaic mirror with 24 trapezoidal (or petal) segments, for another thing, a monolithic mirror is also a candidate for its primary mirror. Both of them depend on active control technique to maintain the optical quality of the ring mirror. As a solar telescope, the working conditions of the CGST are quite different from those of the stellar telescopes. To avoid the image deterioration due to the mirror seeing and dome seeing, especially in the case of the concentration of flux in a solar telescope, large aperture solar projects prefer to adopt open telescopes and open domes. In this circumstance, higher wind loads act on the primary mirror directly, which will cause position errors and figure errors of the primary with matters worse than those of the current 10-meter stellar telescopes with dome protect. Therefore, it gives new challenges to the active control capability, telescope structure design, and wind shielding design. In this paper, the study progress of active control of CGST for its mosaic and monolithic mirror are presented, and the wind effects on such two primary mirrors are also investigated.

Keywords: Solar Telescope, Ring Aperture, Segmented Mirror, Monolithic Mirror, Active Control, Wind Load

1. INTRODUCTION

Chinese Giant Solar Telescope (CGST)[1] is the next generation infrared and optical solar telescope of China. It is first proposed by Yunnan Observatories CAS, National Astronomical Observatories CAS, Purple Mountain Observatory CAS, Nanjing University, Nanjing Institute of Astronomical Optical Technology and Beijing Normal University. The unique feature of CGST is that its primary is a ring with diameter of 8 meter and width of 1 meter, its collecting area is 22 square meters which equals to a 5 meter telescope with full aperture, but its spatial resolution is 8 meter, thus it can observe the fine structure in near infrared bands as ATST and EST do in visible bands. Meanwhile, the hollow and symmetric structure facilitates the thermal control and polarization measurement. It is expected to become a high performance solar telescope with unprecedented spatial resolution and measurement sensitivity for polarization in both the visible and infrared spectrum.

In the current design and development phase, studies of several key points involved in the CGST are ongoing under the support by National Natural Science Foundation of China (NSFC), Chinese Academy of Sciences (CAS) and all the participated units.

As an 8 meter telescope, active control for its primary mirror is one of the crucial techniques to ensure the high spatial image quality of the science requirements of the CGST. A mosaic mirror with 24 trapezoidal (or petal) segments is the major candidate for its primary. In this configuration, due to the mosaic pattern is different from the current full aperture telescopes, besides the edge sensing like most hexagonal segmented mirrors, the tip measurement of each segment along the ring should be supplemented to complete information for active feedback control loop. At the same time, since the

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size of CGST has not exceeded the largest monolithic mirror at present, a monolithic thin mirror is also a candidate for its primary configuration. Wavefront sensing and modal correction technologies involved in deformable active optics are more mature. However, supporting such a narrow flexible ring mirror is more complex and difficult.

Conventional active optics aims to correct the deformation of primary mirror due to the change of gravity direction and thermal effect, which are temporally slow and hence easy to compensate for. As to wind load effects, studies of current 8-10 meter stellar telescopes[1, 2] show that the static wind disturbance can also be covered by the lower bandwidth of gravitational and thermal correction in an active control system, and the residual dynamic wind does not degrade the image quality significantly, thanks to the shielding of a dome or an enclosure the wind speed is reduced to one tenth from its open-air value. However, it is not the case in 8 meter CGST. Wind load effects on primary mirror are more problematic for its expected open air configuration and should be paid more attention from the beginning of the design. It makes important sense to a series of designs including active control loop, support system and wind shielding et al.

In the following sections, we introduce the research progress of the active control for the segmented CGST. Then we present a preliminary support design of the monolithic CGST and its modal analysis. Dynamic analysis of wind load effects on the segmented and monolithic primary mirrors based on the structure design and wind model is provided in Section 4. Conclusions are given in Section 5.

2. ACTIVE CONTROL OF THE SEGMENTED CGST

We have studied and described the active control issues of a segmented ring telescope[4~6] with the ring telescope project evolution[1, 7, 8]. Some important aspects are sketched as follows:

The primary mirror of the CGST is expected to be composed by 24 trapezoidal solid segments of 1 meter square each, for trapezoid-shaped segment is the shape easiest to form a ring aperture.

Three out-of-plane DOFs, piston, tip and tilt, of each segment are adjusted by three actuators below each segment to maintain the image quality of the telescope during operation. The placement of actuators is illustrated in the Figure 1. Mirror figure variance is measured by two kinds of sensors. On one hand, two edge sensors straddled on every neighboring edge like those in existing segmented telescopes are used to measure the edge displacements of every two adjacent segments. On the other hand, since the trapezoidal segment is lack of interlocking ability, tip measurements of each segment along the ring are required to complete the feedback information of the control system. Such a control structure is the same in the phasing process (active alignment) as well as in the active maintenance process. The difference is just determined by the sensor types adopted. For instance, electro-mechanical sensors, such as capacitive or inductive sensors, are commonly used as the edge sensors in the active maintenance, while optical means like the modified Shack-Hartmann [9] or the compact interferometer[10] are used as the edge sensors in the phasing process.

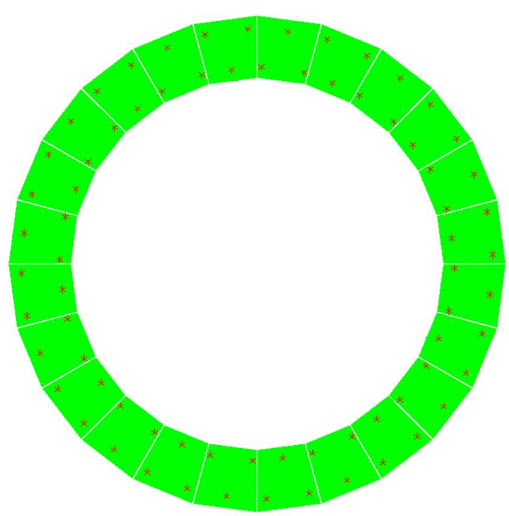

Figure 1. Actuators layout under the primary mirror of the segmented CGST.

Since there are two different measurement techniques in a control loop, the control performance of such a system depends on the mutual matching of edge sensing and tip sensing[5]. On one hand, two kinds of sensing accuracy should be matched. According to the sensors used in the current segmented mirrors, tip sensing accuracy is generally lower than that of edge sensing, thus tip sensing dominates the performance of the control system. Increasing tip sensing accuracy could improve the control performance. Simulations[6] show that the primary mirror of CGST can realize diffraction-limited imaging at wavelength of 1000nm with the combined accuracies of edge sensing and tip sensing of 5nm and 0.01arcsecond (which equals to 25nm when it is converted to edge height in 1 meter square segment). On the other hand, working bandwidth of two kinds of sensing should be matched especially in the process of active maintenance. This is because high accuracy tip sensing by means of optical method usually needs longer integral time, thus the working bandwidth is much lower than that of electro-mechanical edge sensors. Although the bandwidth of active maintenance of the segmented CGST is limited less than 0.3Hz[11] for avoiding the control structure interaction (CSI), this control bandwidth still challenges the limit of tip sensing.

Some relevant key issues involved in tip sensing for CGST are also being studied. In point of Shack-Hartmann type tip sensing, there are two principle factors affecting the sensing accuracy. One is the atmospheric turbulence, the other is measurement algorithm. Besides adopting long time integration, the atmospheric turbulence can be reduced by means of using multi sensing subpupils and shortening the distance between the sensing pupils. A supposed subpupils layout of tip sensing is illustrated in Figure 2. A couple of subpupils for relative tip sensing are located in each side of the segment edges, which makes the baseline of sensing shortest and thus increase the sensing accuracy. Multi-couples along the edge can reduce the atmospheric effects and measurement errors. Internal or external light source are both applicable in this sensing scheme. The advantages of internal light source is that the influence of atmosphere is small and measurement error small, however, a special measurement instrument is needed and supposed to be placed around the position of two times the focal length. As to external light source, it is convenient to implement at the terminals of the telescope, but the influence of atmosphere is more serious, and the measurement accuracy is affected by the observational objects. For example, measurement error is small when the objects locate in the region of solar center and large when the objects locate in the region of solar edge. More detailed study of the relationship between the integral time also associated with working bandwidth and the sensing accuracy is to be done in the next work.

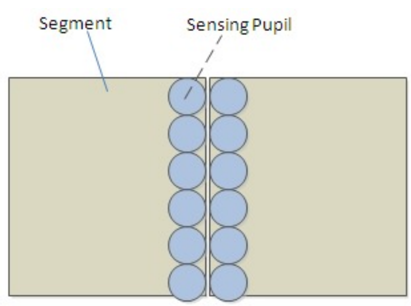

Figure 2. A supposed Shack-Hartmann type tip sensing scheme.

3. RESEARCH PROGRESS ON THE MONOLITHIC CGST

Due to the complexity of detection problem involved in the segmented CGST, also because the size of CGST has not exceeded the largest monolithic mirror of 8 meter, using a thin meniscus ring mirror as primary is also taken into account. From the point of technology, Shack-Hartman sensor wildly used in common adaptive optics (AO) system undoubtedly meets the requirement of deformable mirror active control with relative lower bandwidth. As to the wavefront correction techniques, two modal correction methods have been discussed deeply[12]. One is Zernike annular polynomials, which are the modified Zernike polynomials orthogonal in a ring aperture. The other is annular natural vibration modes, which are also orthogonal in a ring aperture with minimum energy as well, and believed to have advantage working in the active optics corrections of elastically induced errors rather than Zernike annular polynomials. However, deformable mirror active optics also involves difference and difficulty in support system design for an 8-m class monolithic flexible ring mirror. In this paper, we consider a preliminary support design of the thin ring mirror for the dynamic analysis of wind load effects, more detailed support design will be done in the following work.

In reference 11, the segmented CGST was presented with a rocking-chair type mounting. This section discusses a CGST using the same mounting but for a monolitic thin primary of the same aperture instead. For the lateral support, refer to Figure 3, 24 passive hydraulic cylinders are tangently attached to the mirror edge and arranged in three groups. To be exact, every eight cylinders share a standalone hydraulic station, so as to form three virtual fixing points around the mirror to support and define two lateral/in-plane motions and one spinning motion. 96 axial supports - 93 force actuators plus 3 defining points - are used for the deformable active optics. The mirror blank is zerodur and has a thickness of 150 mm. In order to get even better support performance, each of the 96 axial supports is expanded into a quadropod attached on the mirror back. Taking advantage of its rotational symmetry, refer to Figure 4, a 1/24 mirror is modeled with FEM. The calculated RMS surface error is 18 nm.

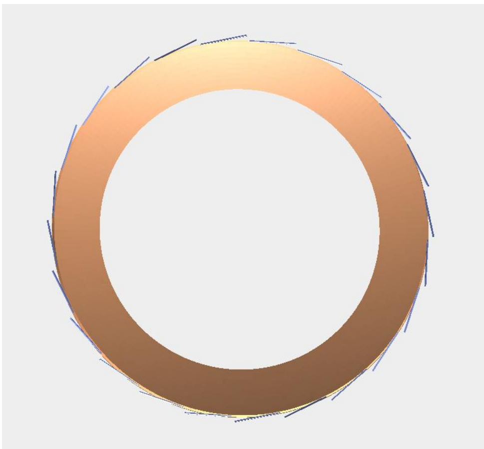

Figure 3. Lateral support concept.

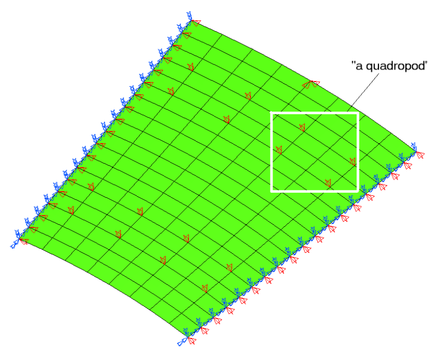

Figure 4. Axial support concept (1/24 FEM) .

A finite element model (FEM) of the full monolithic CGST is established at the elevation angle of 45^{o}.The force actuator is assumed with stiffness of 200 N/mm. The eigenfrequency spectrum of the first 200 modes is extracted and shown in Figure 5. The first two eigenfrequencies of ~7.8 Hz, referred in Figure 6, are dominated by the mirror itself, associate with two astigmatisms. The later frequencies are linearly increasing through the modes, which are observed mostly associating with the tube and spiders.

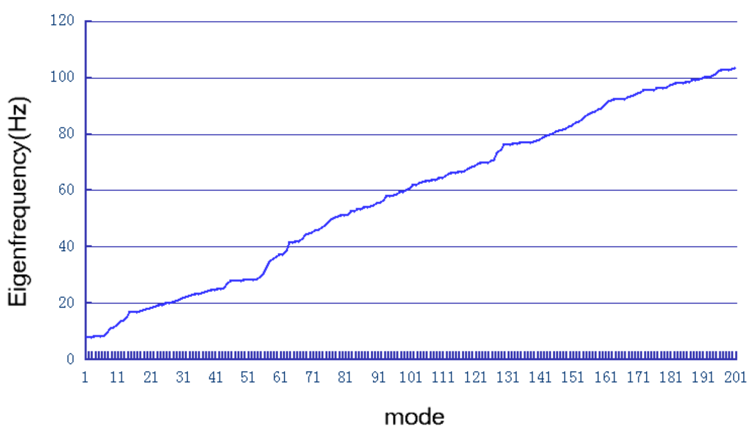

Figure 5. Eigenfrequency spectrum (the first 200 modes) of the monolithic CGST.

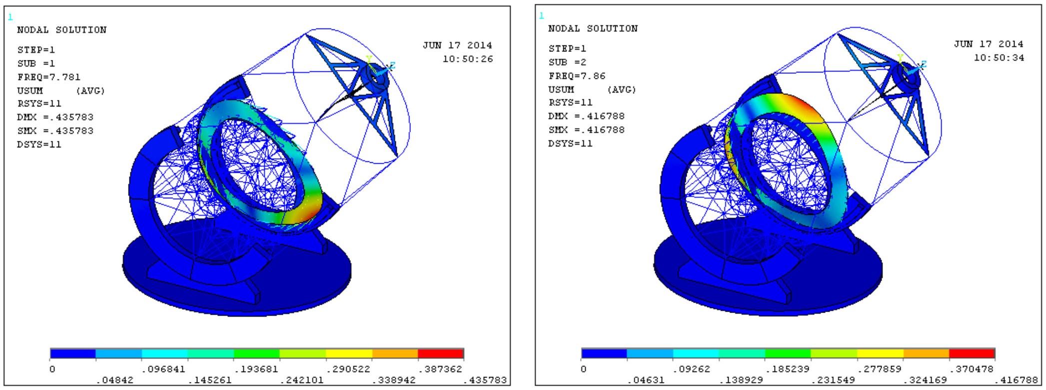

Figure 6. The first two modes dominated by the mirror.

4. WIND LOADS ON THE PRIMARY MIRRORS

Wind loads on a large solar telescope are more serious than those on a stellar telescope with the same magnitude of aperture with the dome protect. To avoid the problem with thermally induced mirror seeing and dome seeing, open telescope structure and open dome observational mode is desirable for most large aperture solar telescope projects. Consequently, higher wind load act on the telescope structure directly, which cause image deterioration through three paths[13,14]: (i) loads on the primary mirror deforming the primary mirror, (ii) loads on the secondary and secondary mirror causing secondary figure and position errors, and (iii) loads on the secondary support structure leading deformations of the primary mirror through structural coupling. The last type of error can be avoided by applying decoupling design between secondary support and primary mirror cell, and the influences from the secondary mirror are the same in the above two primary configurations, therefore, in this paper wind effects on primary mirror are emphasized and investigated based on the preliminary structure models of the segmented and monolithic ring mirror schemes.

4.1 Performance of the segmented mirror

Reference 11 has presented the detailed modeling for dynamic analysis of wind load effects on the segmented CGST, some important aspects are as follows:

The FEM model of the segmented CGST is established at an elevation angle of 45° . The dynamic response of the segmented primary mirror centers to the wind disturbance is obtained through modal superposition using the first 201 modes below 60Hz, which contains the most meaningful local modes associated with tip/tilt and piston of all the 24 mirror segments.

At present phase, a theoretical model is sufficient to predict the performance of the wind load, and a classical wind speed temporal spectrum of Davenport is used to produce the frozen 2D wind screen based on the assumption that the spatial wind velocity spectrum is identical in the direction of the wind flow and perpendicular to that direction. It is formulated as follows:

$$S(f) = \frac{4v_*^2 X^2}{f(1+X^2)^{4/3}}, \tag{1}$$

where

$$X = \frac{(1200m)f}{\overline{v}(10m)}. \tag{2}$$

$\overline{v}$ is the mean wind velocity at a height of 10m above ground, and v_* the friction velocity. The approximate pressure variations can be obtained by Bernouille's law based on velocity fluctuation.

A simple integral controller is used in every modal control loop, and the integral controllers are limited with the same bandwidth for all modes to simplify the analysis. From reference 11, the control bandwidth should be limited below 0.3Hz so as to avoid control instability due to the control-structure-interaction (CSI).

Simulations have been run to give the performance of the segmented CGST under two typical wind loads, a lower wind velocity of 2m/s and a higher wind velocity of 6m/s, on the primary mirror. The statistics of the high wind velocity comes from the measurement records at Fuxian Lake, where the 1-m New Vacuum Solar Telescope is sited[15]. The individual open loop and close loop (with bandwidth of 0.3Hz) response on mean wind velocity of 2m/s and 6m/s are simulated, the mean errors and average RMS errors over the 24x3 nodes representing the 24 mirrors are listed in Table 1. Figure 7 gives the corresponding mirror figures before and after active control.

Table 1. Mean Errors and average RMS errors before and after segmented active control.

	Mean wind velocity 2m/s		Mean wind velocity 6m/s	
	Mean error (nm)	Mean RMS error (nm)	Mean error (nm)	Mean RMS error (nm)
Open loop	293	33	2746	400
Close loop	4	21	39	442

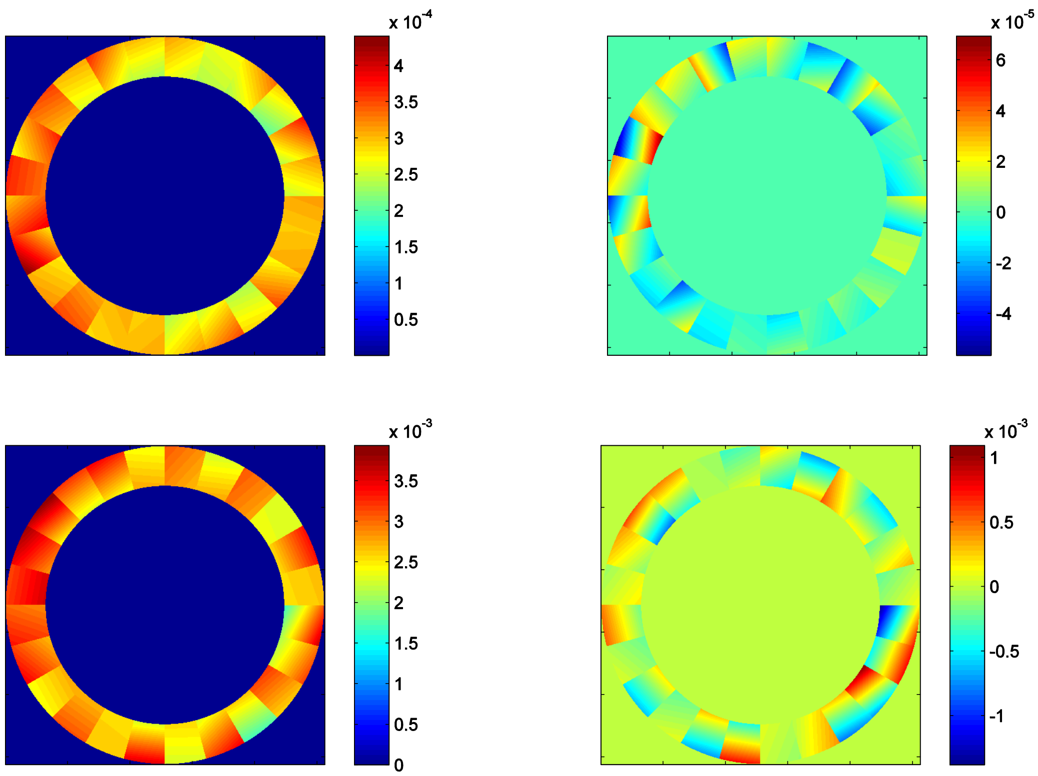

Figure 7. Mirror figures before and after segmented active control, unit of millimeter. The upper left: mirror figure of open loop under mean wind velocity of 2m/s, the upper right: mirror figure of close loop under mean wind velocity of 2m/s, the lower left: mirror figure of open loop under mean wind velocity of 6m/s, the lower right: mirror figure of close loop under mean wind velocity of 6m/s.

4.2 Performance of the monolithic thin mirror

For comparing with the performance of the segmented CGST, simulations of wind load effects on the monolithic thin mirror are carried out under the same wind disturbance and control bandwidth. Bandwidth of 0.3Hz also guarantees not to stimulate the structure resonance. The FEM model of the thin meniscus mirror is also constructed at elevation angle of

45°, and the structure model contains the first 200 modes below 103.5Hz. The individual open loop and close loop performance on mean wind velocity of 2m/s and 6m/s are listed in Table 2, and the corresponding mirror figures are illustrated in Figure 8.

Table 2. Mean Errors and average RMS errors before and after deformable active control.

	Mean wind velocity 2m/s		Mean wind velocity 6m/s	
	Mean error (nm)	Mean RMS error (nm)	Mean error (nm)	Mean RMS error (nm)
Open loop	35	82	327	782
Close loop	8	24	81	243

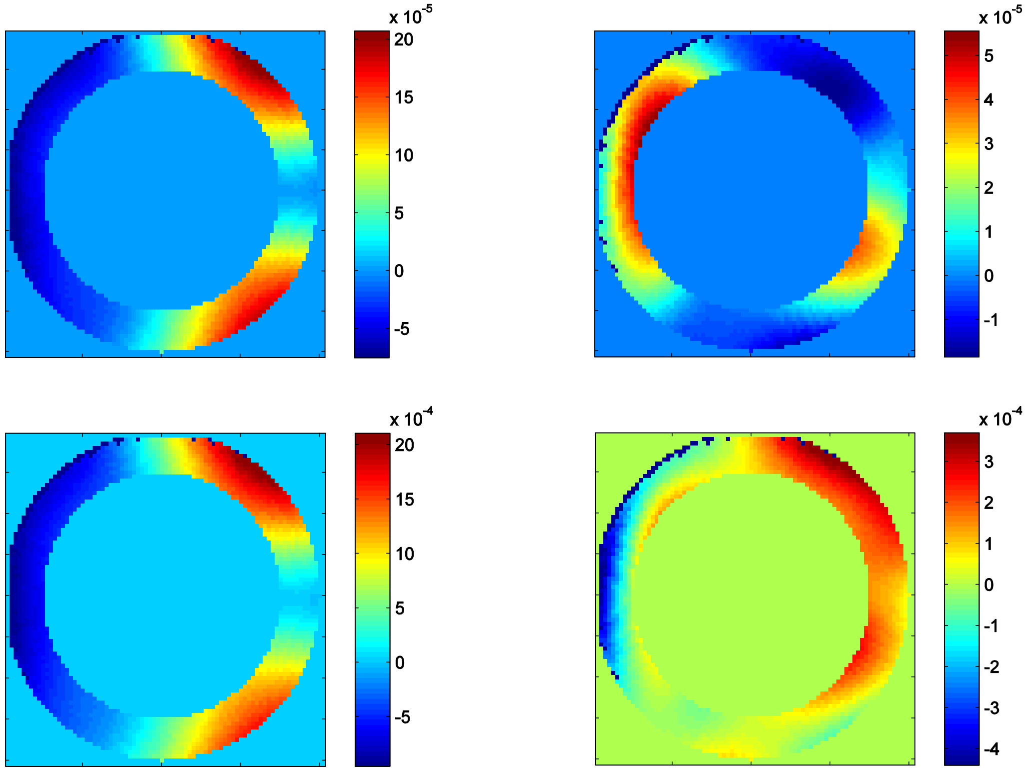

Figure 8. The same as Figure7, but with deformable active control.

4.3 Discussions

The dynamic analysis of CGST show that in the case of low wind velocity, active control with bandwidth of 0.3Hz can correct the static wind disturbance and part of wind buffeting, the residual dynamic wind will not affect the mirror figure significantly; while for high wind velocity, due to the wind energies in high frequencies increasing, active control with the same bandwidth can only compensate part of the static wind disturbance and is not efficient to compensate the dynamic wind loads. A higher bandwidth controller is preferred, but it is still limited by the requirement of avoiding the CSI. Consequently, the stiffness of the telescope structure and primary mirror support should be maximized. Meanwhile, an appropriate wind shield is needed.

It is also worth mentioning that the residual error on the monolithic thin mirror is dominated by the low spatial frequency errors, which is easier to compensate by the subsequent AO system with higher bandwidth as long as it is within the capture range of AO system. In contrast, the residual error on the segmented mirror is high spatial frequency error with edge discontinuity, which is difficult to capture by AO system. As a result, wind buffeting on the segmented CGST is more dangerous than that on the thin meniscus CGST, a wind shield is indispensable in the segmented scheme.

5. CONCLUSIONS

The study progress on the active control of CGST is presented in this paper. In the segmented active control, employing tip sensing with high accuracy additional to edge sensing is the significant difference from that using in the other full aperture segmented telescopes, which increase difficulties in implementation. However, manufacture of the segment about 1 meter square is easier. In the deformable active optics, control related techniques are more mature, but supporting, manufacture and transportation of such narrow thin ring mirror are more difficult. They each have pros and cons, the final decision of the pattern of the primary mirror needs more detailed working. Furthermore, in open air condition, wind loads effects on the primary mirror of 8m class should not be underestimated, an appropriate wind shield even enclosure is needed.

6. ACKNOWLEDGEMENTS

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