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ADJUSTABLE BIPOD FLEXURES FOR MOUNTING MIRRORS IN A SATELLITE TELESCOPE

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Abstract: A new mirror mounting technique applicable to the primary mirror in a space telescope is presented. Conventional bipod flexures for mounting mirror bosses are changed to have mechanical shims to adjust gravitational distortions at the mirror surface. Analytical results using finite element methods are compared with experimental results from an optical interferometer. Vibration tests qualified their use in space applications.

Keywords: mirror mount, optomechanics, flexures, tolerance, space optics.

1. INTRODUCTION

Optical systems require support structures that isolate the optical parts from mechanical loads. Mechanical loads are gravity, vibration, assembly or mounting errors, and fabrication residual stress. The performance of optical mirrors, such as those employed in satellite telescopes, may be severely degraded by an inappropriate mounting configuration. The general design objective and philosophy of an optical mirror mount are introduced by Chin [1]. The concepts for a successful mounting should minimize optical distortions and provide a simple means of alignment. A kinematic mount is an ideal support constraining three orthogonal axes without redundancy. However, the point contact desirable for a kinematic support is not feasible in environmentally challenged systems. Instead, a semi-kinematic mount with a finite contact area is usually adopted to disperse local stresses. Flexure mounting may be regarded as a semi-kinematic design. A flexure is a monolithic structure providing elastic motions in a predefined way. The benefits of using flexures include lack of the hysteresis and the friction effects inherent in semi-kinematic mounts. Also, maintenance is unnecessary and fabrication has become common practice with electrical discharge machining. A mirror mount flexure is not intended for linear or precise motions. Different from the flexure hinges used in actuator mechanism, a mirror mount flexure minimizes optical surface distortions and maintains optical alignment under operation or transport. Kinematic principles determine the location and the direction of a mounting flexure. The line of action of the flexure should pass through the mirror’s center of gravity. Compliance should be provided to athermalize the mirror and mounting flexures. For example, radial compliance should be added in an axisymmetric mirror element. Tangential compliance is also required to prevent assembly stress from propagating toward the mirror surface [2]. Lateral mirror supports are usually responsible for radial and tangential compliance. Axial mirror supports, in the case of massive large aperture telescopes, reduce mirror surface distortion.

Flexure mounts can be categorized according to the type of flexure element. Simple blade flexures are usually used as tangential edge supports for relatively small axisymmetric mirrors [2]. A bipod flexure, which is the most common support type, generally gives better results in terms of optical performances [3, 4]. Conventional bipod flexures are made monolithically and are used as lateral supports. The angle of the bipod flexure or the height of the apex formed by the bipod should be aligned in such a way that the mirror's surface distortion due to gravity can be minimized. However, the fabrication tolerance of a glass-ceramic mirror is relatively high compared with a metallic substrate due to the inherent manufacturing limitation. Slight deviations of the mirror's dimensions result in a change of mass center and inertial moments. And combined with fabrication and assembly errors of the bipod flexures, the mirror's surface distortion cannot be minimized as expected. If the deviation is too large or unacceptable, a new set of bipod flexures should be made to compensate for mirror's fabrication errors. This procedure is, however, time-consuming and costly. Also it is risky to remove structural adhesives coupling the mirror and bipod flexures and to replace with a new flexures.

This paper describes a new bipod flexures having mechanical shims to adjust gravitational distortions at the mirror surface. Even when there are inevitable fabrication and assembly errors deviating from nominal design values, the mirror's gravitational distortion can be adjusted and minimized by replacing mechanical shims with a suitable thickness. Also gluing the mirror with flexures is once and for all, which is desirable for mirror's safety. Section 2 describes the principles and configurations of the new bipod flexure system. Section 3 explains the performance of the flexure with theoretical and experimental results. Section 4 shows the results of vibration tests and verifies its application in space optical system. Section 5 concludes this paper.

2. PRINCIPLES

The configuration of bipod flexures mounting a primary mirror is shown in Fig.1. The mirror is fabricated having lightweight pockets at the back surface. It has three square bosses extruded at the mirror's rim for flexure mounting. The flexure is coupled with the mirror by using an epoxy adhesive. Contrary to the monolithic bipod flexures, this flexure has three components. Flexure A is fixed onto the mirror's boss permanently by using an adhesive. The flexure B is fastened to the flexure A with threaded bolts and locating pins. A shim is located in the middle between flexure A and flexure B and can be changed with a suitable thickness to adjust the mirror's distortion due to gravity. The apex of the triangle formed by a bipod flexure should point to the mass center of the mirror or equivalently shear center of the mirror in order to minimize the surface distortions due to gravity. A small amount of misalignment makes the mirror surfaces have astigmatic wavefront error.

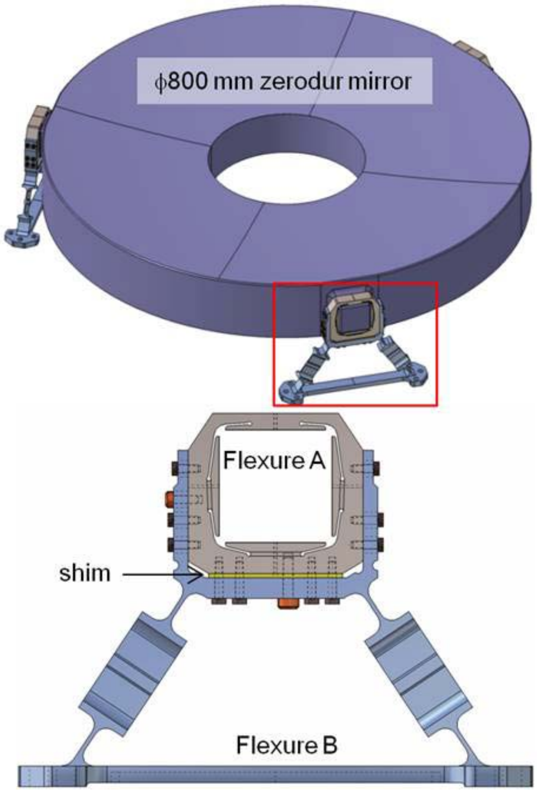


Fig. 1 ϕ800 zerodur mirror mounted on bipod flexures is shown. The bipod flexure is composed of flexure A, flexure B and a shim. The shim can be changed easily to adjust mirror surface distortions.

Fig. 2 shows the measurement setup of the mirror using an optical interferometer. The mirror and the optical interferometer are aligned parallel to the ground or perpendicular to the gravity direction. This horizontal configuration is preferred by the space optical systems during the whole process of fabrication, assembly, and optical performance testing. Extracting non-gravity surface figure is possible by rotating the mirror with respect to the optic axis and combining the results thereof. The optical distortion due to gravity should be minimized as much as possible in order to reduce the difference between the ground-based testing and non-gravity optical performance in outer space. Once the mirror is fabricated within the design tolerance, surface distortion due to gravity can be adjusted by changing shim thickness in Fig. 1.

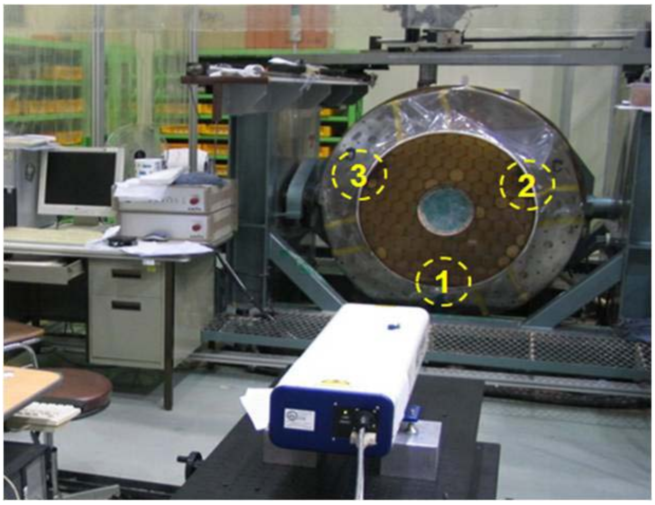


Fig. 2 Interferometric testing of ϕ800 zerodur mirror in horizontal position. The numbers superimposed in the figure indicate the locations of each flexure glued at the mirror bosses.

3. OPTICAL PERFORMANCE

Surface distortions at the mirror surface can be simulated by using finite element analysis. Surface errors with respect to the shim thickness change are shown in Fig.3. The shim thickness can be changed from zero, which means no shim, to 4 mm which is the maximum thickness. Peak-to-valley (PV) value and root-mean-square (RMS) values are also shown. Zernike terms Z5, which is astigmatism about x, has a linear relation with the shim thickness. Z5 is almost zero at nominal thickness of 2 mm. Z5 is 25.3 mm when shim thickness is 1 mm, and Z5 is -24.3 mm when shim thickness is 3 mm. This relation can be used as a lookup table for finding optimum shim thickness to minimize mirror's distortion due to gravity.

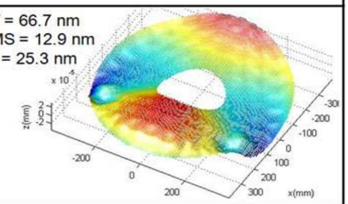
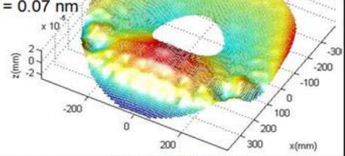
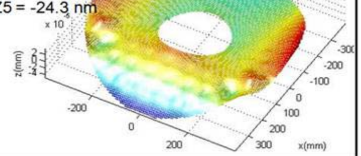
Shim Thickness	Surface Error
1 mm	PV = 66.7 nm RMS = 12.9 nm Z5 = 25.3 nm 
2 mm	PV = 49.1 nm RMS = 6.7 nm Z5 = 0.07 nm 
3 mm	PV = 87.5 nm RMS = 12.2 nm Z5 = -24.3 nm 

Fig. 3 Variations of the mirror surface error map with respect to the shim thickness. Shim thickness can be changed from zero, which means no shim, to 4 mm which is the maximum thickness.

Fig. 4 show the plots of z5 term with respect to the shim thickness obtained from experiments using an optical interferometer and computer simulations using FEA. Even if the z5 plot from experiments slightly deviates from the linearly expected one, the nominal shim thickness, which is 2 mm, proved to be the optimum value minimizing astigmatic errors due to gravity.

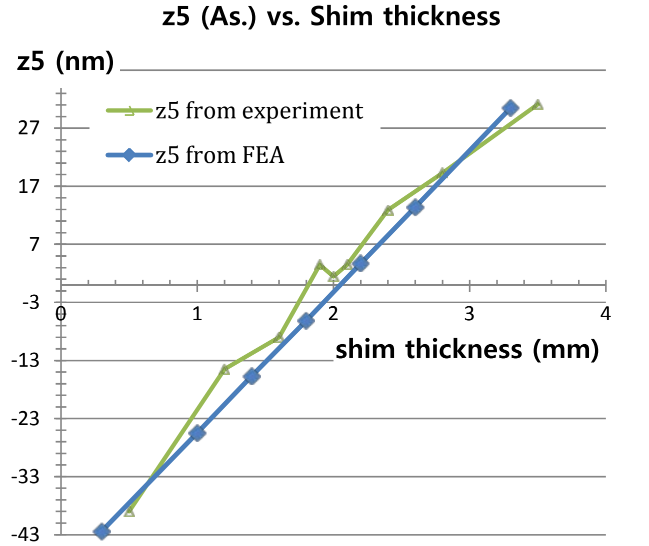


Fig. 4 z5 (astigmatism) terms with respect to the shim thickness are shown.

System error in terms of rms is also minimum at the nominal shim thickness as shown in Fig. 5. The best rms value is 12 nm from experiments and 7 nm from FEA. The theoretical minimum value only accounts for the surface distortion due to gravity. The discrepancy between two rms values can be ascribed to other system error sources such as null lens error, interferometer error, and environmental disturbances. In other words, the best obtainable surface error with the current mirror system design, when the mirror polishing is perfect, is limited by 12 nm rms. Fig. 6 shows the systematic error only from the gravity effect.

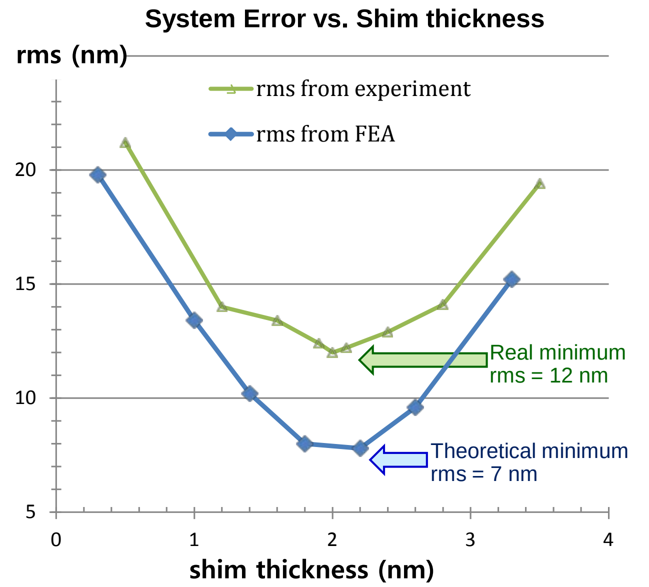


Fig. 5 System errors due to gravity in rms are plotted with respect to the shim thickness. The minimum rms value obtained from experiments is 12 nm, which is higher than theoretical value of 7nm.

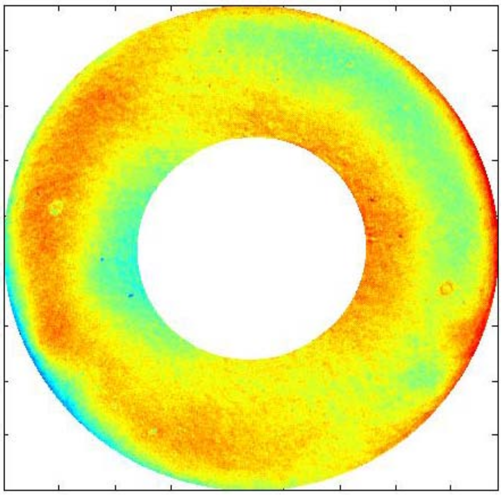


Fig. 6 Systematic error due to gravity effect is 12 nm in rms.

3. VIBRATION TESTS

We verified the applicability of the adjustable bipod flexure to the flight model system with vibration tests. Compared with a monolithic flexure, the proposed flexure is composed of many mechanical parts including fasteners, which lowers the reliability and durability. The vibration test verifies the mechanical safety under launch loads and optical stability before and after the test.

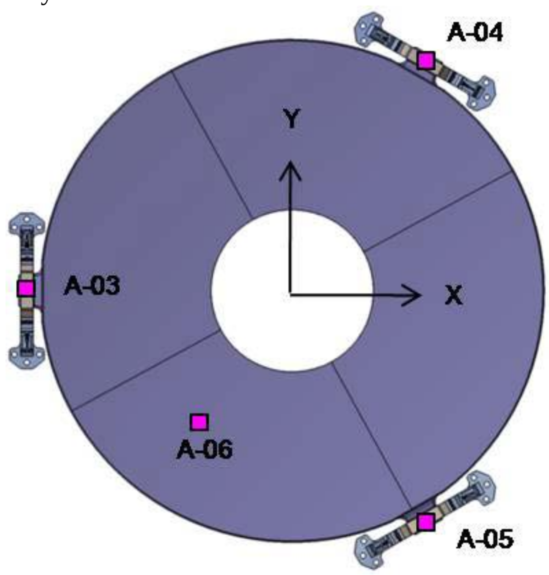


Fig. 7 D800 mirror system with accelerometers.

Fig. 7 shows the coordinate of the mirror system and the locations of accelerometers. Their positions were selected by using FEA for ideal dynamic detection. Table 1 shows the random vibration profile applied to the mirror system. Fig. 8 shows the D800 mirror system loaded on a shaker for vibration tests.

Axis	Frequency	ASD	Duration
X, Y, Z	20 Hz	0.0143 g^2/Hz	60 sec
	70 Hz	0.0500 g^2/Hz	
	400 Hz	0.0500 g^2/Hz	
	2000 Hz	0.0100 g^2/Hz	
	7.1 grms		

Table 1 Random vibration profile and specification

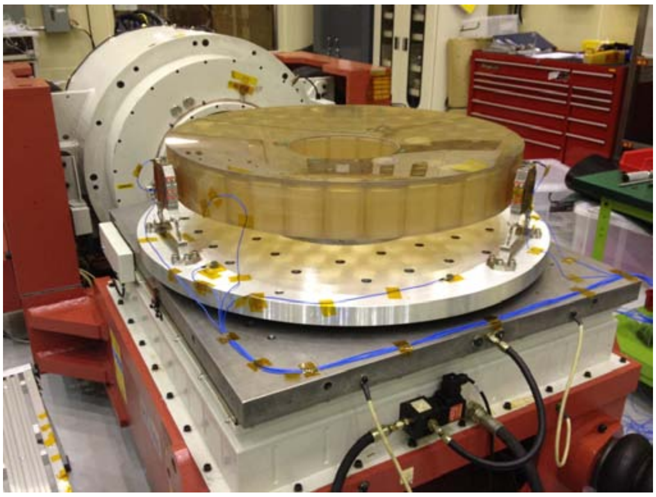


Fig. 8 D800 mirror system on a shaker for vibration tests.

Table 2 lists the modal frequencies obtained by FEA and vibration tests. Their deviations are less than 1 % satisfying the requirement of 5 %. The vibration tests were conducted successfully, and there was no change in modal frequencies before and after the tests. There was no substantial change in surface figures after the vibration test.

	Prediction (Hz)	Test (Hz)	Deviation	Req.
X-mode	196	194	1.0 %	< 5 %
Y-mode	196	198	1.0 %	
Z-mode	305	307	0.7 %	

Table 2 Comparison of modal frequencies obtained from each axis.

4. CONCLUSIONS

We presented a new mirror mounting technique applicable to the primary mirror in a space telescope. Conventional bipod flexures for mounting mirror bosses are changed to have mechanical shims to adjust gravitational distortions at the mirror surface. Analytical results using finite element methods are compared with experimental results from an optical interferometer. Vibration tests qualified their use in space applications.

5. REFERENCES

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