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Optomechanical Design of Compact Laminar Flexure Bending Mechanism for Elliptically Bent Hard X-ray Mirrors

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Abstract. As a part of the Argonne Strategic Partnership Project (SPP) 85E77, collaboration between Argonne National Laboratory (ANL) and Shanghai Institute of Applied Physics (SINAP), has produced designs for a precision compact flexure bending mechanism to provide elliptically shaped 90-mm and 160-mm long hard x-ray mirrors. The design utilizes Argonne's laminar nanopositioning flexure technique. The flexure mirror bending mechanism will be incorporated into the beamline upgrade project at the Shanghai Synchrotron Radiation Facility (SSRF). Additionally, an Argonne Laboratory-Directed Research and Development (LDRD) project at the Advanced Photon Source (APS) has adopted a modified optomechanical design of the precision compact mirror benders for 300-mm-long hard x-ray mirrors with integrated profile monitoring and feedback, which are described in this paper. The mirror benders are designed with configurations for open-loop or closed-loop controls. Capacitive sensors can be applied to the mirror benders to ensure positioning reproducibility. Design specifications as well as finite element analyses results of the compact mirror benders for hard x-ray mirrors with trapezoid and rectangular shapes are discussed in this paper.

INTRODUCTION

The Advanced Photon Source (APS) at Argonne National Laboratory (ANL) is a 7 GeV national user facility for synchrotron radiation research. The 3.5 GeV Shanghai Synchrotron Radiation Facility (SSRF) at the Shanghai Institute of Applied Physics (SINAP) is a third generation synchrotron radiation source. Both APS and SSRF have a keen interest in the development of novel Kirkpatrick-Baez (K-B) mirror [1] mount stages for synchrotron radiation applications. As a part of the Argonne Strategic Partnership Project (SPP) 85E77, collaboration between ANL and SINAP has produced several designs of precision compact flexure bending mechanism for elliptically bent hard x-ray mirrors using Argonne's laminar overconstrained nanopositioning flexure technique [2-5].

The dynamic mirror benders can be tuned to high precision mirror figures across a wide range of incidence angles. This enables one to optimize the focusing and transmission of the mirrors to cover a wide energy range, especially for x-ray focusing optics coated with multilayers in a K-B configuration [6,7]. Meanwhile, the compact, cost-effective flexure mirror benders with high stability are also suitable for regular x-ray mirrors with various metal coatings for many x-ray optics applications. In this paper, we present the optomechanical design of the precision compact mirror benders using Argonne's laminar overconstrained flexure mechanism with 90-mm, 160-mm, and 300-mm-long hard x-ray mirrors for hard x-ray nanofocusing and hard x-ray zoom optics applications at the SSRF and APS.

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DESIGN OF THE DYNAMIC MIRROR BENDER FOR 90-MM-LONG MIRROR

The first proof-of-principle prototype of the miniature dynamic mirror bender with laminar overconstrained flexure mechanism is designed for a SSRF 90-mm-long x-ray mirror. It is constructed with closed-loop control configuration for mechanical and optical test. The mirror bender has a pair of laminar flexure mechanism modules and a pair of bending arms. A Newport™ NPM-140 piezo micrometer adapter with 90 micron travel range [8] is installed for the short bending arm along with two manual adjusters for both long and short bending arms. Figure 1 is a Photograph of the Z7-5006 prototype dynamic mirror bender with closed-loop control configuration.

The flexure bending mechanism module is constructed with stacks of thin metal weak-link sheets which are manufactured using photochemical machining processes with lithography techniques [2]. With the same flexure bending mechanism module, and using two Newport™ Picomotor™ 8301 actuators, the Z7-5006 miniature dynamic mirror bender can also be configured for open-loop control with more cost-effectiveness.

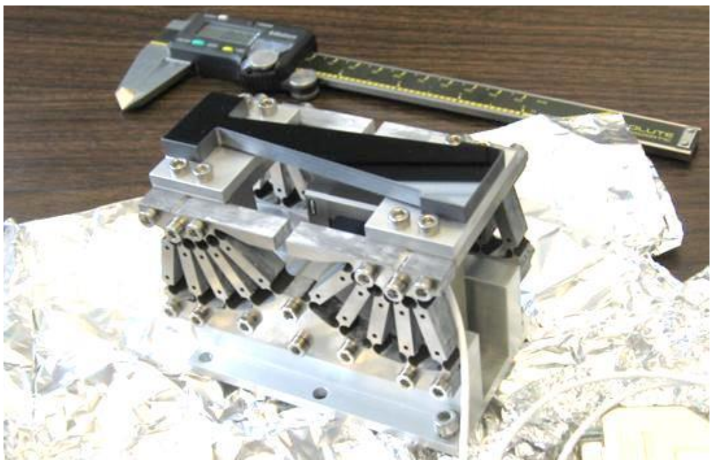


FIGURE 1. Photograph of the Z7-5006 prototype dynamic mirror bender with closed-loop control configuration. The 90 mm long silicon mirror has an effective optical length of 66 mm and thickness of 5.5 mm. The width of the mirror is designed to perform the optical figuring of the mirror under bending [7]. With a tunable bending moment between 0.35 N·m to 0.71 N·m, the elliptical mirror figure radiuses are tunable between curvatures of 24 m–88 m to 12 m-44 m. It has been tested at the SSRF optics lab with long trace profiler (LTP). A ~350 nm FWHM 1-D focusing using Z7-5006 miniature mirror bender with 90-mm-long mirror has been observed at the SSRF undulator beamline BL15U.

DESIGN OF THE DYNAMIC MIRROR BENDER FOR 160-MM-LONG MIRROR WITH CAPACITIVE SENSORS ON THE BENDING ARM

To gain the design flexibility for longer mirror, the prototype of the dynamic mirror bender Z7-5005 with closed-loop control configuration for 160-mm-long x-ray mirror has been designed with new Z7-5005 bending mechanism module, which is constructed with two separate stacks for left and right sides bending arms as shown in Figure 2.

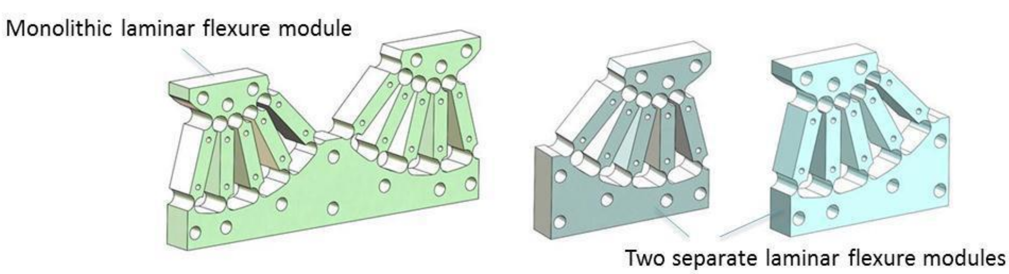


FIGURE 2. Comparison between 3D models of the monolithic laminar flexure module for Z7-5006 miniature mirror bender with 90-mm-long mirror and the Z7-5005 separate flexure modules design with flexibility for longer mirrors.

The mirror bender Z7-5005 is designed for a 160-mm-long trapezoid mirror for SSRF beamline upgrade project. The mirror bender includes a base, two pair of laminar flexure mechanism modules, a pair of bending arms, and two Newport™ Picomotor™ 8301 actuators [8] for both bending arms. Two sets of capacitive sensors (probe model C5R with CPL290 readout electronics from Lion Precision™) [9] are applied on both bending arms to ensure the bender's positioning reproducibility as shown in Figure 3.

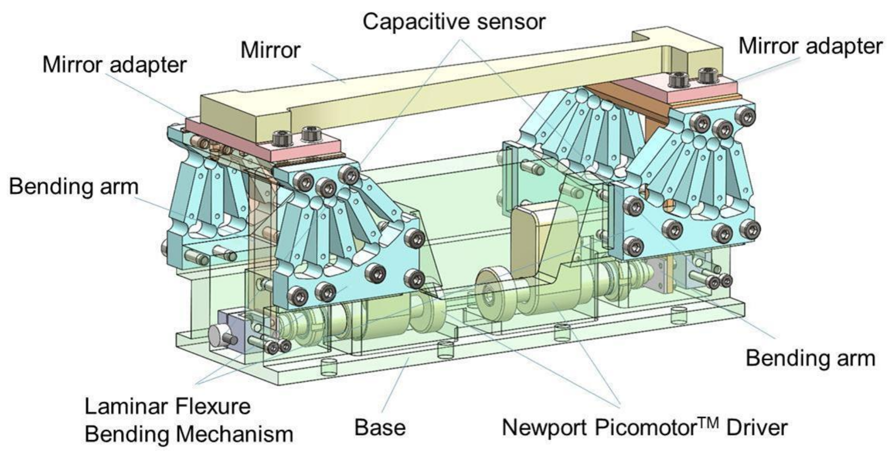


FIGURE 3. A 3D model of the miniature dynamic mirror bender Z7-5005 for SSRF 160-mm-long trapezoid x-ray mirror. Two sets of capacitive sensors are applied on both bending arms for closed-loop positioning control.

DESIGN OF THE DYNAMIC MIRROR BENDER FOR 300-MM-LONG MIRROR FOR ARGONNE ZOOM-OPTICS

Design of the Prototype Dynamic Mirror Surface Profile

As a part of the Argonne Laboratory-Directed Research and Development (LDRD) project at the APS, a dynamic mirror bender Z7-5004 is designed and under construction to perform initial test for x-ray zoom optics using deformable mirrors with in situ wavefront sensing and a closed-loop mirror profile control. The 300-mm-long elliptical mirror figure should be tunable between radiuses curvatures of ~0.525 – ~74 km as shown in Figure 4.

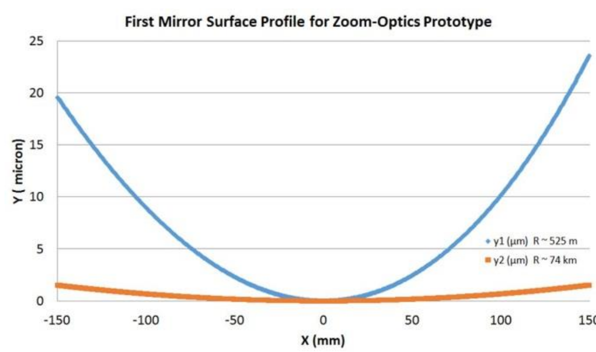
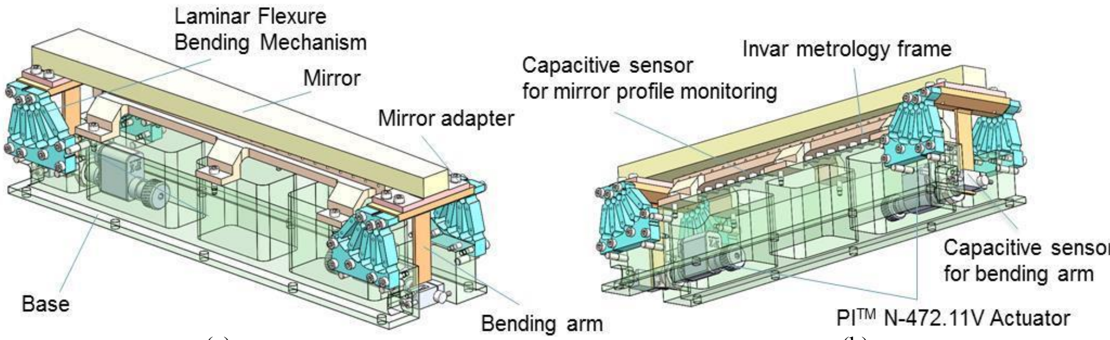


FIGURE 4. Design requirement for the 300-mm-long mirror for Argonne zoom optics project: the elliptical mirror figure should be tunable between radiuses curvatures of ~0.525 – ~74 km.

Design of the Z7-5004 Mirror Bender and Optional Invar Metrology Frame with Capacitive Probes

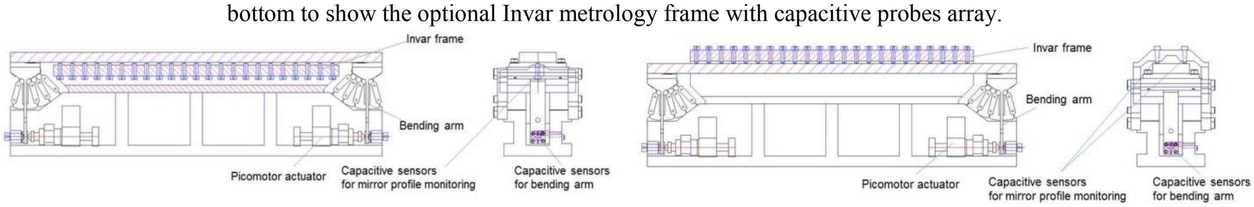
Similar to the Z7-5005 bending mechanism, the mirror bender Z7-5004 module for 300-mm-long mirror is constructed with two separate stacks for left and right sides bending arms with ultrahigh positioning sensitivity and stability. As shown in Figure 5, the mirror bender Z7-5004 consists of a base, two pair of laminar flexure mechanism modules, and a pair of bending arms. The bending arms for Z7-5004 are driven by PI™ N-472.11V closed-loop PiezoMike™ linear actuators and monitored by two sets of capacitive sensors (probe model C5R with CPL290 readout electronics from Lion Precision™) to ensure the bender's positioning reproducibility.

To further monitor and control the mirror profile, an Invar frame with an array of capacitive sensors (probe model C3R with CPL290 readout electronics from Lion Precision™) are designed as an optional metrology attachments for the mirror benders Z7-5004 as show in Figure 6. The capacitive sensor array will afford this design with a high degree of shape control and reproducibility.



(a) (b)

FIGURE 5. (a) A 3D model of the Z7-5004 mirror bender and the optional Invar metrology frame with capacitive probes array for 300-mm-long mirror for Argonne zoom optics project. (b) A 3D model of the Z7-5004 mirror bender with view from bottom to show the optional Invar metrology frame with capacitive probes array.



(a) (b)

FIGURE 6. (a) Diagram of the side and front views of the Z7-5004 mirror bender with Invar metrology frame with a single linear array of capacitive probes to monitor the surface of the mirror back. (b) Diagram of the side and front views of the Z7-5004 mirror bender with Invar metrology frame with two linear arrays of capacitive probes to monitor the mirror optical surface.

Finite Element Analyses for the Z7-5004 Mirror Bender

Preliminary Finite Element Analyses (FEA) for Z7-5004 compact mirror bender showed that the combination of two bending moments are able to produce an elliptically bent trapezoid mirror surface to fit with desired mirror figure radius of curvature of ~74 km within a 4 nanometer tolerance over the 87% of the 300 mm full mirror length. With the same trapezoid mirror, in the case of desired elliptical mirror figure radius of curvature of ~0.525 km, the FEA showed results within 5 nanometer and 9 nanometer tolerances over the 50% and 87% respectively of the 300 mm full mirror length. With a 300-mm-long rectangular mirror, the FEA showed a result to fit with desired elliptical mirror figure radius of curvature of ~0.525 km within an 8 nanometer tolerance over the 47% of the 300 mm full mirror length.

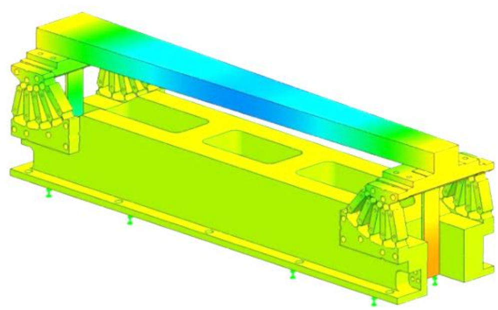


FIGURE 7. 3D model of the FEA vertical displacement result for Z7-5004 compact mirror bender with 300-mm-long elliptically bent trapezoid mirror.

SUMMARY

Optomechanical design of compact laminar flexure bending mechanisms for 90-mm, 160-mm, and 300-mm-long elliptically bent hard x-ray mirrors are presented in this paper. The mirror benders are designed with configurations for open-loop or closed-loop controls. A prototype of the miniature dynamic mirror bender with closed-loop control configuration for 90-mm-long x-ray mirror has been designed, constructed, and tested with LTP and x-ray at the SSRF for beamline upgrade project in 2017.

Capacitive sensors can be applied to the mirror bender bending arms to ensure bender's positioning reproducibility. To further monitor and control the mirror bending condition, an Invar metrology frame with array of capacitive sensors is designed as an optional metrology attachment for the mirror bender Z7-5004 for 300-mm-long hard x-ray mirror. A prototype of the Z7-5004 mirror bender with Invar metrology frame with array of capacitive sensors is under construction for test at the APS with LTP and x-rays for Argonne LDRD project for zoom optics and the APS Upgrade project.

Table 1 summarizes the design specifications of the compact laminar flexure mirror benders for 90-mm, 160-mm, and 300-mm-long elliptically bent hard x-ray mirrors.

TABLE 1. Design specifications of the laminar flexure mirror benders Z7-5006, Z7-5005, and Z7-5004

Laminar flexure mirror bender Z7-5006 for 90-mm-long mirror	
Overall dimensions (mm)	90 (L) x 62 (W) x 25 (H)
Mirror dimensions (mm)	90 (L) x 25 (W) x 5.5 (T)
Type of the bending actuator (for one bending arm)	Newport^{TM} NPM-140
Maximum bending moment (N·m)	6.6
Bending actuator minimum incremental motion (nm)	1
Laminar flexure mirror bender Z7-5005 for 160-mm-long mirror	
Overall dimensions (mm)	160 (L) x 78 (W) x 72 (H)
Mirror dimensions (mm)	160 (L) x 30 (W) x 8 (T)
Type of the bending actuator (for one bending arm)	Newport Picomotor^{TM} linear actuator 8301
Maximum bending moment (N·m)	1.4
Bending actuator minimum incremental motion (nm)	30
Type of the capacitive sensors for bending arm	Lion Precision^{TM} C5R-2.0 with CPL290
Resolution of the capacitive sensors for bending arm (nm)	1.5
Laminar flexure mirror bender Z7-5004 for 300-mm-long mirror	
Overall dimensions (mm)	308 (L) x 82 (W) x 82 (H)
Mirror dimensions (mm)	300 (L) x 30 (W) x 12 (T)
Type of the bending actuator (for one bending arm)	PI PiezoMike^{TM} N-472.11V
Maximum bending moment (N·m)	1.4
Bending actuator minimum incremental motion (nm)	50
Type of the capacitive sensors for bending arm	Lion Precision^{TM} C5R-2.0 with CPL290
Resolution of the capacitive sensors for bending arm (nm)	1.5
Type of the capacitive sensors for Invar metrology frame	Lion Precision^{TM} C3R-0.8 with CPL290
Resolution of the capacitive sensors for metrology (nm)	0.5

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REFERENCES

1. Kirkpartrick, P. and Baez, A. V. Formation of Optical Images by X-Rays. JOSA. 1948; 38(9): 766-773.
2. U.S. Patent granted No. 6,607,840, D. Shu, T. S. Toellner, and E. E. Alp, 2003.
3. U.S. Patent granted No. 6,984,335, D. Shu, T. S. Toellner, and E. E. Alp, 2006.
4. D. Shu, T. S. Toellner, E. E. Alp, J. Maser, J. Ilavsky, S. D. Shastri, P. L. Lee, S. Narayanan, and G. G. Long, AIP CP879, 1073-1076 (2007).
5. D. Shu, A. Li, S. P. Kearney, C. Mao, J. Anton, and Y. Pan, Proceedings of MEDSI 2016, Barcelona, Spain.
6. R. Barrett, J. Härtwig, C. Morawe et al, Synchrotron Radia-tion News, 23, No.1, 36-42 (2010)
7. A. Li and C. Mao, Private Communications (2016)
8. http://www.newport.com/Picomotor-Piezo-Linear-Actuators/
9. http://www.lionprecision.com