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Surface Slope Metrology on Deformable Soft X-ray Mirrors

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Abstract. We report on the current state of surface slope metrology on deformable mirrors for soft x-rays at the Advanced Light Source (ALS). While we are developing techniques for *in situ* at-wavelength tuning, we are refining methods of *ex situ* visible-light optical metrology to achieve sub-100-nrad accuracy. This paper reports on laboratory studies, measurements and tuning of a deformable test-KB mirror prior to its use. The test mirror was bent to a much different optical configuration than its original design, achieving a 0.38 micro-radian residual slope error. Modeling shows that in some cases, by including the image conjugate distance as an additional free parameter in the alignment, along with the two force couples, fourth-order tangential shape errors (the so-called *bird* shape) can be reduced or eliminated.

Keywords: x-ray, KB mirror, bender, surface slope, wavefront measurement, at-wavelength, *in situ* testing
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INTRODUCTION

Nano-focusing and brightness preservation are challenging goals shared by x-ray scientists worldwide. While the accuracy of *ex situ* mirror bending techniques has improved over time, wavefront control on beamlines is often limited by environmental and systematic alignment factors. At the Advanced Light Source (ALS), we are developing broadly applicable, high-accuracy, *in situ,* at-wavelength wavefront measurement techniques to surpass 100-nrad slope measurement accuracy for Kirkpatrick-Baez (KB) mirrors [1]. At the same time, we are refining and optimizing *ex situ* mirror bending methods essential for nano-focusing and for feedback to improve the manufacturing process.

The at-wavelength methodology we are developing relies on a series of tests with increasing accuracy and sensitivity. Geometric Hartmann tests, performed with a scanning illuminated sub-aperture determine the wavefront slope across the full mirror aperture [2]. Shearing interferometry techniques use coherent illumination and provide higher sensitivity wavefront measurements [3]. Combining these techniques with high precision optical metrology and experimental methods will enable us to provide *in situ* setting and alignment of bendable x-ray optics to realize sub-50-nm focusing at beamlines. We are now creating a beamline endstation configured specifically for the development of high accuracy at-wavelength measurement methods; these techniques will ultimately allow closed-loop feedback systems to be implemented for x-ray nano-focusing.

Due to limited capture tolerances, most *in situ* techniques will not be applicable without accurate pre-alignment of the mirror elements. This paper presents laboratory studies, measurement and tuning of a single deformable KB test-mirror prior to its use on a beamline. This mirror, originally designed for hard x-ray applications, was successfully repurposed for higher NA, soft x-ray nanofocusing.

For our measurements, we are using a single KB mirror element that was originally designed for a different application: sub-μm x-ray fluorescence and diffraction studies. Since our goal is to investigate nano-focusing and wavefront metrology, we decided to increase the numerical aperture (NA) far beyond the mirror's original design specifications, giving it a smaller diffraction-limited spot size. Initially, it was not clear that the mirror could be accurately bent into this new shape. Using long-trace profilometry, we investigated the bending to determine whether sub-μrad RMS residual slope errors could be achieved.

PROPERTIES OF THE MIRROR AND BENDER

Mechanical Details

Table 1 presents the optical design parameters of this mirror as it was originally intended, and as we are using it—with a larger, 8 mrad, grazing incidence angle. With the larger incidence angle, the radius of curvature becomes considerably smaller.

TABLE 1: The original and desired design specifications of the KB mirror under test. The mirror is a silicon substrate with 4 mm thickness, 102-mm length, and an 80-mm clear aperture.

Mirror design	Mirror center radius of curvature	Object distance	Image distance	Grazing angle
original	57.14 m	2400 mm	120 mm	4.0 mrad
desired	27.91 m	1600 mm	120 mm	8.0 mrad

The mirror-bending mechanism is based on two cantilever springs (Fig. 1). Each cantilever spring is connected by wire to a displacement-reduction spring driven by a *Picomotor*. Displacement of the Picomotor actuators is monitored with linear variable differential transformers (LVDT) with an accuracy of approximately 100 nm. The bender design allows for extremely fine control of the bending force couples applied to the mirror substrate.

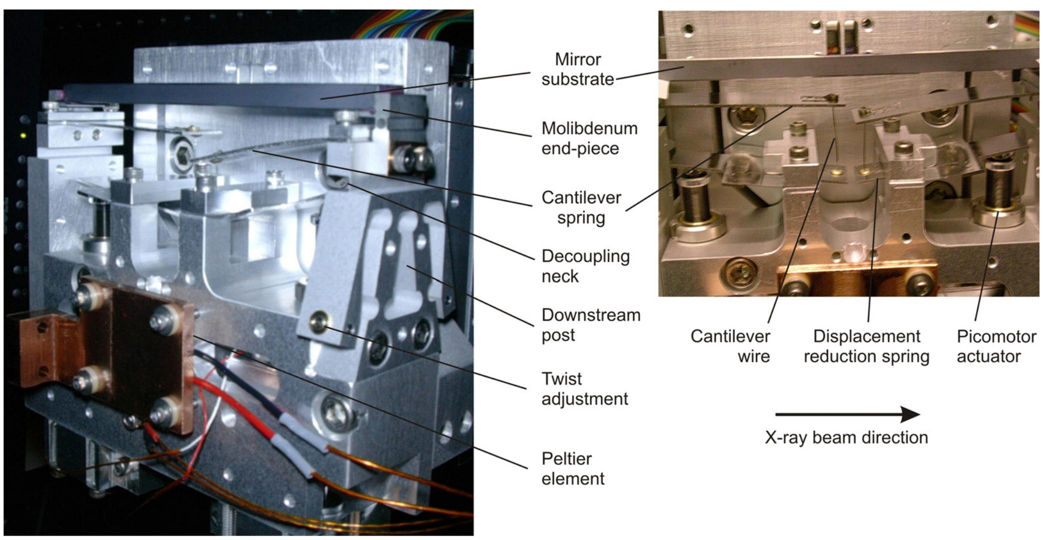


FIGURE 1. The KB mirror mounted in its bender mechanism.

Precision Assembly and Preliminary Bending

The assembly and preliminary mirror bending were performed by monitoring the mirror surface shape with a ZYGO GPI interferometer in the ALS Optical Metrology Laboratory (OML) [4].

First, with relaxed cantilever springs, the mirror substrate and its glued molybdenum end-blocks is attached to the bender mechanism. The downstream post is tightened to the mirror body, while the upstream post is loosened. Final positioning and tightening the upstream post is made in a way to provide the smallest possible curvature of the installed substrate. The upstream post has two decoupling flexures that decrease the stress applied to the mirror substrate due to assembly error. The downstream post is equipped with an anti-twist mechanism and has one decoupling flexure. The thickness of the flexures is about 0.015 in. (380 μm), and does not provide complete stress decoupling. As a result, the radius of curvature due to residual stress is about 500 m (concave) after initial installation.

Second, the twist in the mirror substrate is removed with the dedicated downstream anti-twist adjustment shown in Fig. 1. The anti-twist mechanism is designed with its axis of rotation on the reflecting surface of the mirror.

Third, a ZYGO interferometer is used to measure the tangential radii of curvature from three sections of the mirror's clear aperture (upstream, central, and downstream). The mirror is bent to a shape close to the desired ellipse. In our lab, the ZYGO's measurements are limited to a relatively large radii of curvature. Therefore, its measurements are only used to confirm that the benders have the required range of tuning.

Finally, the anti-twist correction process is repeated for the central part of the bent mirror. Later, a final, more precise anti-twist correction will be performed with the Developmental Long Trace Profiler (DLTP) [5, 6] observing the entire clear aperture of the mirror.

OPTICAL METROLOGY AND TUNING

Tuning Techniques

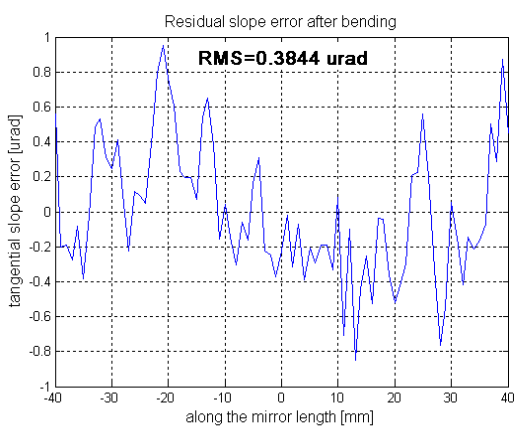
The mirror is precisely set with the DLTP by measuring and removing substrate twist and by fine-tuning to the desired elliptical tangential shape using the mirror bending mechanism. The original procedure used to set the mirror bending was developed at the OML and is described in detail in Refs. 7 and 8.

Profilometry of the Mirror under Optimal Tuning

Figure 2a shows the mirrors' residual tangential slope error after subtraction of the desired elliptical shape. The RMS slope error is approximately 0.38 μrad, primarily due to a fourth-order surface shape error (third-order in the slope), and fine-scale residual slope errors due to the substrate's surface structure and possibly the DLTP. The noise level is reduced by averaging four consecutive measurements.

We believe that the residual third-order slope error arises from the fact that the mirror was designed with different optical parameters (see Table 1). Below third order, we have shown that the two bending force couples can effectively remove the residual slope aberrations [7, 8]. Mirror substrate pre-stress is another possible source of residual shape error. Stress can perturb the shape of the mirror via the known tension effects discussed, for example, in Ref. 9.

(a)



(b)

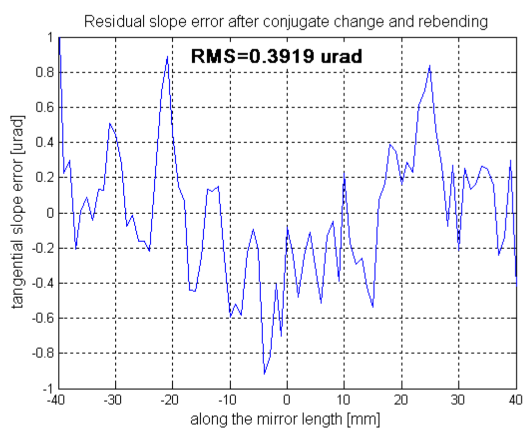


FIGURE 2. The residual slope error of the mirror tangential slope after subtraction of the desired elliptical shape, measured in the sagittal center of the mirror, and averaged over four consecutive measurements. (a) At 120 mm image conjugate distance, the residual error is mainly comprised of a third-order slope shape and mid-scale surface roughness. (b) Adjusting the image conjugate distance to 118.82 mm and re-bending eliminated the third-order slope error, albeit with negligible change in the RMS error magnitude in this case.

Numerical modeling showed that we could eliminate the third order slope error by altering the image conjugate distance and adjusting the two force couples. Reducing the image distance from 120.00 mm to 118.82 mm and re-bending produced the residual slope error shown in Fig. 2b. Although in this case the RMS magnitude is equivalent to within our measurement uncertainty, this approach to removing fourth-order shape errors (i.e. third-order slope errors) should be broadly applicable. Within some range of useful values, the image conjugate distance provides an additional degree of freedom for error minimization in pursuit of nano-focusing and coherence preservation.

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