Experimental methods for optimal tuning of bendable mirrors for diffraction-limited soft x-ray focusing

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Abstract. We report on hands-on experimental methods developed at the Advanced Light Source (ALS) for optimal tuning of mechanically bendable x-ray mirrors for diffraction-limited soft x-ray nano-focusing. For ex situ tuning of the benders for optimal beam-line performance, we use a revised version of the method of characteristic functions recently developed at the ALS optical metrology laboratory. At-wavelength optimal tuning of bendable optics consists of a series of wavefront-sensing tests with increasing accuracy and sensitivity, including modified scanning-slit Hartmann tests. The methods have been experimentally validated at ALS test beamline 5.3.1 and the micro-diffraction beamline 12.3.2 in applications to optimally set bendable Kirkpatrick-Baez mirrors designed for sub-micron focusing.

1. Introduction

At the Advanced Light Source (ALS), plans for remaking of many of the original beamlines, some of which are now almost 20 years old, are developing. Replacement of a beamline is a costly enterprise, and hence it takes considerable time to raise the necessary funds. In parallel with this long term program, we are developing ideas for a short term program to improve the performance of the ALS beamlines with modest improvements of the optical systems, leaving the basic beamline structure and design intact. The cost of this program that we call Light Source Upgrade of X-ray Optics for Research (LUXOR) is estimated to be on average 10% of the cost of a new beamline, and in some cases, performance increases of several orders of magnitude can be gained [1]. Within the scope of the LUXOR initiative, we have started a program to develop ex situ and in situ experimental methods for optimization of beamline performance of x-ray optics at the ALS [2-4]. Here, we report on hands-on experimental methods developed at the ALS optical metrology laboratory (OML) for optimal tuning of mechanically bendable x-ray mirrors for diffraction-limited soft x-ray nano-focusing.

2. Ex situ tuning of bendable focusing x-ray optics for optimal beam-line performance

In Refs. [5-7], an experimental method for optimal setting of bending couples of bendable x-ray optics has been suggested and thoroughly discussed. The method utilizes ex situ optical slope metrology for obtaining characteristic functions of the bending couples that describe the response of the mirror surface shape to a unit change of the couples. With the characteristic functions experimentally determined, the surface slope deviation from the desired shape is minimized by optimizing the values of the applied bending couples. Mathematically, for the optimization, linear regression analysis is used, assuming an equal contribution of the mirror surface points to the final beamline performance of the optic.

Here, we extend the method to account for different statistical weights of the surface slope errors for different positions along an x-ray focusing elliptically-shaped mirror. The problem becomes important for beamlines, such as the ALS micro-diffraction beamlines 10.3.2, and 12.3.2, where the distance from the mirror to the focal plane is comparable with the size of the optic. Optimization of beamline performance of a mirror consists of minimizing the variance of ray errors in the focal plane,

$$\delta s(x) = 2 \cdot r'(x) \cdot \delta\varphi(x)\,, \tag{1}$$

rather than minimization of the square of the residual (after subtraction of the ideal shape) surface slope error $\delta\varphi(x)$. In Eq. (1), $r'(x)$ is the distance from a point x of the mirror surface to the image side focus. For high quality x-ray optics, $r'(x)$ can be approximated by the value corresponding to an ideally shaped mirror (no surface errors).

In the case of an elliptical mirror, its shape is described with a set of conjugate parameters: the distance to the mirror center $(x = 0)$ from the object side focus, r_0, and from the image side focus, r_0', and the value of the grazing incidence angle α_0. The parameters are uniquely related to the canonical parameters of the ellipse (see, e.g., Ref. [8]). Using the relation between the canonical parameters and the corresponding focal distances of an ellipse (see, e.g., Ref. [9]), one can derive the dependencies of the focal distances on the position along an elliptical mirror:

$$r(x) = r_0 + x\cdot Cos\alpha_0 \text{ and } r'(x) = r_0' - x\cdot Cos\alpha_0\,. \tag{2}$$

The latter expression in Eq. (2) has the interpretation of being the desired weighting function to be substituted in Eq. (1) and used for optimization of the beamline performance of the mirror.

In order to carry out the optimization based on Eqs. (1) and (2) with the existing OML algorithm and software [2,3], we apply regression analysis to the traces $s(x) = 2(r_0' - x\cdot Cos\alpha_0)\cdot\varphi(x)$, generated from the measured surface slope distributions $\varphi(x)$, rather than to the slope distributions themselves. Correspondingly, from the alterations of the generated traces, resulting from a change of each mirror bender couple $dC_{1,2}$, the characteristic functions of the benders in the terms of the generated traces, $f_{C1,C2}(x) = ds_{C1,C2}(x)/dC_{1,2}$, are found. The characteristic functions are used to fit by linear regression the difference between the trace, generated from the surface slope measurements, and the desired trace, $s_0(x) = 2(r_0' - x\cdot Cos\alpha_0)\cdot\varphi_0(x)$, where $\varphi_0(x)$ is the surface slope distribution of a mirror with the ideal elliptical shape. The result of the fitting is the values of the optimal adjustments ΔC_1 and ΔC_2. These adjustments must then be applied to the mirror benders in order to tune its surface to the shape that corresponds to the best beamline focusing with the mirror.

If a bendable mirror is perfectly designed to provide exact adjustment to the ideal shape, the procedure, discussed above, will not lead to a change of the optimal couples. However, the ideal design is very difficult to realize practically. More often, the bent mirrors have a residual figure error described with a 'bird' shape. In the slope domain, the 'bird' shape is seen as a third order polynomial – Fig. 1 (see also Ref. [8]). Figure 1 shows the residual slope trace measured with the optimally set vertically deflecting mirror [10] used at the ALS test BL5.3.1 for the project to develop hands-on wavelength metrology methods for diffraction limited focusing [2-4]. The beamline operates with x-rays in the energy range from ~1 to 13 keV. The parameters of use of the BL 5.3.1 Kirkpatrick-Baez (KB) pair are presented in Table 1 together with the evaluated diffraction limited full-width-at-half-maximum (FWHM) beam waist of 150·λ nm and 360·λ nm in the vertical and in the horizontal directions, respectively. Optimization of the BL5.3.1 mirrors with weighting functions compensates the ray errors depicted in Fig. 2. Figure 2 shows the difference between the ray errors predicted for the mirrors optimally tuned at the OML with and without use of the weight function given by Eq. (2). For mirror M2, r_0' is close to the size of the clear aperture. As a result, at $\lambda < 0.5$ nm, the peak-to-valley magnitude of the compensated error of ~80 nm exceeds the diffraction limited vertical focal size.

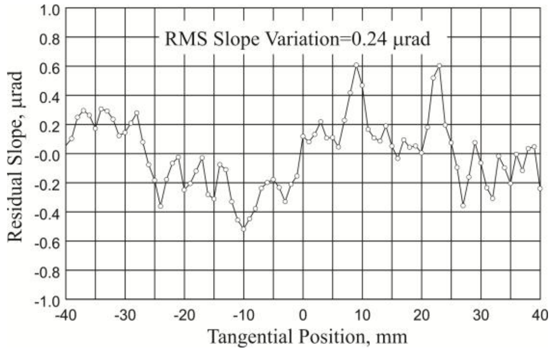

Figure 1. Residual slope profile of the BL 5.3.1 vertically deflecting elliptically-shaped focusing mirror M2 (Table 1). The third-order polynomial-like figure would be seen as a "bird" shape in the height profile of the mirror.

Table 1. Parameters of the use of the BL5.3.1 bendable KB mirrors.

Mirror	r_0, mm	r_0', mm	α_0, mrad	CA, mm	$2NA$, mrad	$\lambda / 2NA$
M2 (vert.)	1650.96	119.39	8.0	80.0	6.55	150·λ nm
M1 (hor.)	1525.76	244.59	8.0	80.0	2.79	360·λ nm

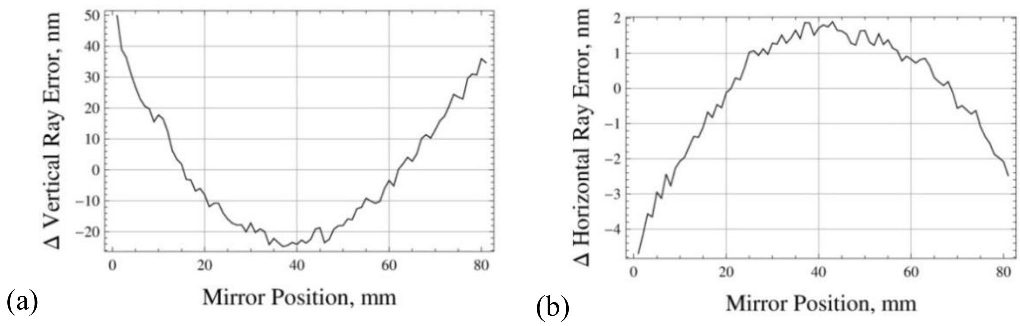

Figure 2. Difference between focal plane ray errors predicted for the vertical (a) and horizontal (b) mirrors (Table 1), optimally tuned with and without accounting the weighting functions.

3. Use of ex situ measured characteristic functions for in situ tuning of bendable mirrors

In situ fine tuning of bendable mirrors is performed in scanning slit experiments [4,11] by measuring the focal plane ray errors as a function of the transverse position u of the slit. The optimization algorithm is the same as that for the ex situ tuning, discussed in Sec. 2. It utilizes the characteristic functions obtained by taking the difference of traces of the ray errors, arising from a unit change of the corresponding bender coupling. Once the characteristic functions are measured, we find the optimal bender settings by linear regression analysis. For suitable precision we require many measurements of the ray error traces to average out the random, systematic and drift errors of the measurements.

The procedure, discussed in Sec. 2, allows significant shortening of the time required for in situ tuning of benders, by generating the characteristic functions from existing ex situ optical slope metrology data. First, using an expression for an ellipse in the polar coordinate system centered in the object focus [9], an analytical formula for $x(u)$, interrelating the position on the mirror surface x with the position of the slit u, is derived. Then, the ray error characteristic functions are generated by substituting $x(u)$ into Eqs. (1) and (2) with slope profiles measured ex situ.

Figure 3 demonstrates the excellent agreement between the ray error characteristic functions, measured with a series of scanning slit tests, and ones, generated from the ex situ slope measurement.

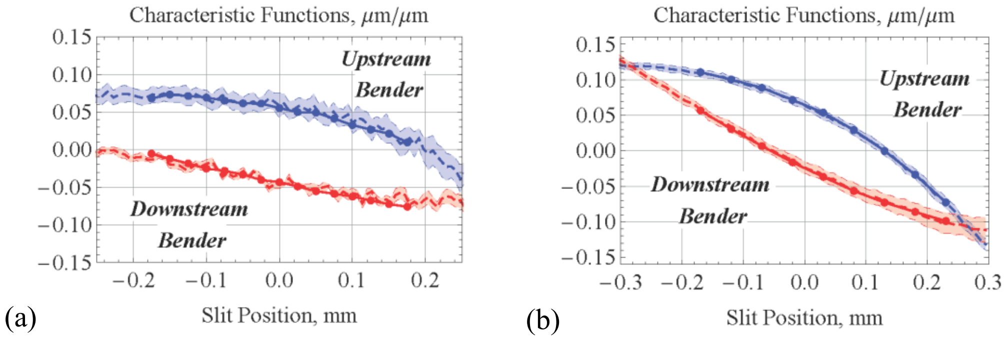

Figure 3. Generated (dashed) and measured (solid) focal plane ray error characteristic functions of the benders for the BL 5.3.1 vertically (a) and the horizontally (b) focusing mirrors. The shaded regions indicate the standard error for the generated characteristic functions.

Conclusions

The method of characteristic functions for optimal ex situ tuning of bendable x-ray mirrors has been extended to account for different statistical weights of the surface slope errors along a mirror. With an example of a horizontally deflecting mirror at ALS test BL5.3.1, it has been demonstrated that application of the method corrects the focal ray error with the peak-to-valley magnitude of ~80 nm that exceeds the diffraction limited horizontal focal size at photon wavelengths $\lambda < 0.5$ nm. Optimal tuning of similar mirrors in use at the micro-diffraction beamline 12.3.2 improves mirror limited focal spot size by a factor of approximately two.

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