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COMPACT MIRROR BENDER WITH SUB-NANOMETER ADAPTIVE CORRECTION CONTROL

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Abstract

We present a compact mirror bender with dynamic surface correction. The system is the evolution of an in-house development and will be the default focusing system for the new ALBA beamlines. The bender is now more compact and can introduce stronger curvatures, as required for microfocus applications. It allows for in-situ correction of the mirror surface, with resolution and stability below one nanometer. The bender can compensate parasitic deformations caused by thermal bumps, changes of focus, or stresses appeared during installation or bakeout.

INTRODUCTION

Surface quality of optical elements is essential to reach the performance of X-ray beamlines in 3rd and 4th generation synchrotron light sources and free electron lasers [1]. Mirror figure errors are usually the limit for the smallest achievable spot on sample and for the resolution of soft x-ray monochromators. In addition, they also limit the homogeneity of defocused beams [2,3]. In the last years, deterministic surface figuring techniques have been developed [4, 5], and sub-nanometer figure errors can be achieved by some mirror polishers [6]. On the other hand, beamline operation often requires certain adaptability: being able to change the focus position, tune the spot size, or compensate thermal bumps. This pushes for the development of active optics systems for x-ray mirrors, keeping the accuracy within the nanometer.

Existing active X-ray optical systems control the topography of the mirror surface by introducing deterministic deformation of its substrate. There are several systems that, to do this with sufficient resolution, use piezo-electric actuators [7-10]. Alternatively, the system we propose controls the deformation by applying point forces distributed along the substrate using spring-based mechanical correctors [11,12]. In order to achieve the required range, resolution, and stability of the applied force, we use a combination of springs and magnets as the elements generating the force.

Results obtained with a prototype demonstrate that the required mechanical performance is achieved, and is stable within several days.

SYSTEM DESCRIPTION

The mirror bender system we propose consists of three main parts: the frame that supports the bending actuators and the correctors, the bender actuators, that support and bend the mirror by applying forces at the ends of the mirror substrate, and the correctors, that apply smaller forces at discrete points along the mirror (see Fig. 1). The whole system is ultra-high-vacuum (UHV) compatible.

The main frame consists of two thick plates that offer a stiff reference for the supports and for the correctors. The plates have multiple slots to allow placing the correctors at any position along the mirror substrate. The two bending actuators are located at the ends of the frame. They support the mirror and provide the bending forces. These actuators are designed to be compact in the direction of the beam, so the complete system is just 20 mm longer than the mirror substrate, and most of the length of the substrate is also clear to install correctors, or cooling pads. The bending actuators include the supports of the mirror, as well as the contacts that apply the bending force on the mirror. All these elements have rolled articulations to minimize parasitic forces that could be applied to the mirror substrate. In particular, all contact points between the bender and the mirror are free to pitch and roll, except one of the supports of the mirror, which is fixed in roll. This fixes the orientation of the mirror but avoids introducing any parasitic twist. Also, all contact surfaces are cylindrical, in order to have a reproducible contact point on the mirror, with acceptable contact stress.

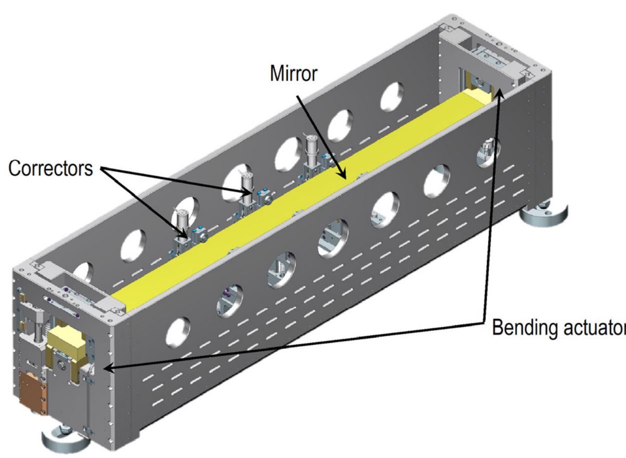

Figure 1. Illustration of the bender prototype, indicating the positions of the bending actuators and of the point correctors.

The bending force applied to each end of the mirror substrate is generated by compressing two helical springs which are connected on one end to a linear stage driven by a stepper motor, and to the mirror on the other end. In addition, the link between the spring and the mirror includes a load cell that provides feedback of the force applied to the mirror. The load cell is placed between braided cables, that compensate any misalignment that could introduce errors on the measurement of force. The load cell resolution is 0.01 N, which corresponds to a 0.5% error in a 100 km

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radius mirror. The resolution of the actuator is actually 0.00055 N per motor step. On the other hand, the maximum force the bender actuators can apply is 1000 N, enough to bend a mirror to a radius in the order of few hundred meters.

The correctors are mechanical modules that can be attached to the frame of the bender, underneath the mirror substrate, and that apply a force normal to the mirror surface. The force is generated by stretching a long spring and is transmitted to the mirror by a lever that can pull or push the mirror, depending on the configuration of the spring. The link between the lever and the mirror is also articulated to minimize any parasitic force, and all articulations are rolled to minimize friction. The width of the corrector is minimized to 22 mm, to allow allocating many correctors. The stretching of the spring is controlled by a simple linear motion system, motorized by a stepper motor.

The force applied by each corrector is stabilized against mechanical drifts of the mirror or support, by a pair of magnets installed at one end of the lever arm. The total force applied to the mirror is the sum of the forces exerted by the spring and by the magnets. However, while the spring force increases with the elongation, the magnetic force decreases with the gap (see Fig. 2). So, mechanical drifts of the mirror with respect to the corrector, which alter equally the elongation of the mirror and the gap between magnets, provoke force drifts of opposite sign on the spring and magnets. The gap between the magnets can be adjusted to match the stiffness of the spring at the nominal position of the mirror, so that the force drifts of the spring are exactly compensated by those of the magnets. Once the magnets are adjusted, the force applied to the mirror can be tuned by adjusting the elongation of the spring, using the corresponding stepper motor. This provides stability of the mirror correction against drifts occurred during installation, transport or during operation.

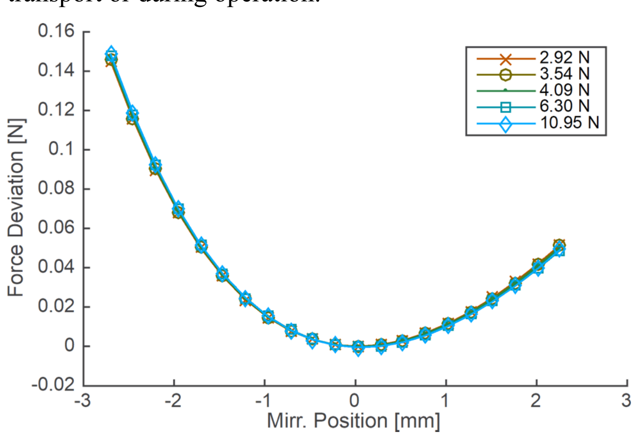

Figure 2. Deviation of the corrector force as a function of the position of the application point, measured for 5 different values of the nominal force.

The force stabilization solution has been tested in a laboratory prototype. In this case, the force applied by the corrector is measured by a load cell, with a resolution of 0.001 N. The position of the application point is scanned using a motorized linear stage. The load cell is placed between the linear stage and the mirror contact of the corrector, which is the force application point. In order to test the stability of the point where the system is stable, the same experiment is repeated for different elongations of the spring, which are adjusted using the stepper motor of the corrector.

The corresponding results are given in Fig. 2. There, the deviation from the nominal force is represented as a function of the position of the application point. One can see that the force deviation presents a minimum at the mirror nominal position, and that in a range of 2 mm around it, the total drift of the force stays below 0.02 N. Note also that the position of such minimum does not depend on the nominal force. This means that once the magnet gap is optimized, the nominal force can be tuned by changing the elongation of the spring, while preserving the position where the stability is optimal.

The mechanical performance of the correctors has been characterized in a test bench that measures the force applied by the corrector. In particular, the resolution of the actuator has been proved to be better than 0.001 N, as shown in Fig. 3.

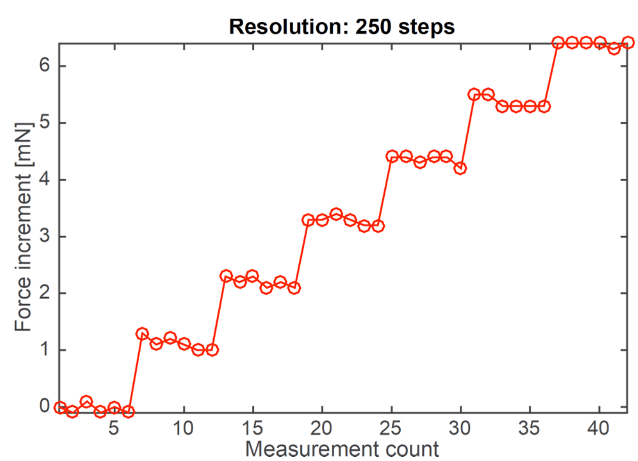

Figure 3. Resolution test results of the corrector.

CORRECTION RESULTS

The correction principle has been demonstrated in a prototype of the system. A mirror with a figure error of 23 nm rms (root mean square), equivalent to a slope error of 0.87 µrad rms, has been corrected to 0.86 nm rms (0.115 µrad rms) (see Fig. 4). Only four actuators at optimal longitudinal positions have been required for this case. The correction is based on the surface height profile as measured by the ALBA-NOM. The difference between the reached figure and the target figure (blue line) is 0.08 nm rms.

We have also verified that the correction is preserved when the radius of curvature of the mirror is changed. Fig. 5 shows measurements of the residual height profile for three different radii of curvature of the mirror. The total variation of the radius is 35%. One can see that the three

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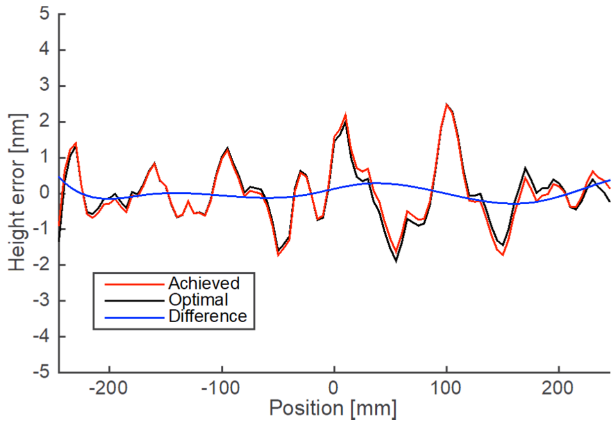

Figure 4. Mirror figure correction. The red line shows the achieved correction. The black line corresponds to the best possible figure according to the deformation model. The blue line corresponds to the difference among the two. The shadowed regions around the blue and red line indicate the repeatability of the measurement.

measurements overlap each other within the nanometer. The different measurements were taken in a lapse of 5 days, which indicates that the correction is also stable in that period of time.

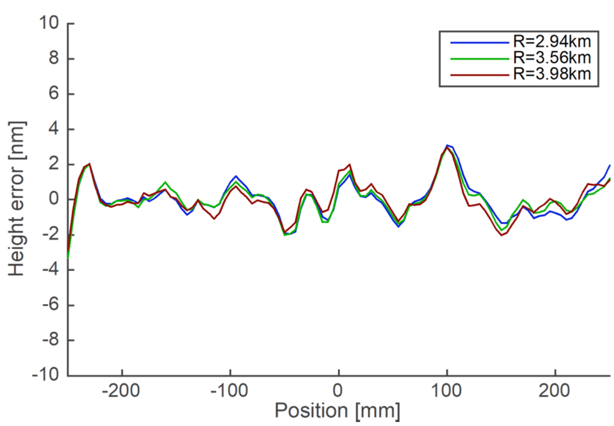

Figure 5. Residual height profile for three different radii of curvature. Corresponding to a difference of 35%.

CONCLUSION

We present a mechanical mirror bender capable of correcting the figure errors below 1 nm rms. The system is fully UHV compatible, and special care has been taken on minimizing the dimensions of the system.

The mirror bender provides bending actuators with force feedback, capable of bending the mirror to the required elliptical figure. In addition to the main bending actuators, the system has additional figure correctors that introduce local deformation of the mirror substrate. The system has been designed to provide high stability of the obtained figure by stabilizing the forces applied on the mirror in front of possible dimensional drifts of the mechanics.

A prototype has been optimized to surface error of 0.86 nm rms, starting from a moderate quality mirror blank. The residual figure error corresponds to high spatial frequencies. The agreement between the achieved results and the theoretical optimal profile agree within 0.08 nm rms. And the correction is shown to be stable in front of changes of curvature as well as in time.

ACKNOWLEDGEMENTS

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