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Long-trace profiler for neutron focusing mirrors

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ABSTRACT

A long-trace profiler (LTP) optimized for measuring the shape of large neutron supermirrors has been designed and built. This LTP can measure 1.6 m long mirrors in both vertically and horizontally deflecting geometries, which is essential to achieve best performance from bendable mirrors. The LTP suppresses the influence of angular deviations of the linear-stage carriage during translation with a pentaprism and a cylindrical lens. The stationary optical head and the carriage-mounted pentaprism are precisely aligned to rotate about the optical axis between the two components. This feature allows measurements to be made on mirrors mounted vertically, horizontally or at any angle in between. The LTP software allows for rapid optimization of parameters for dynamically bent elliptical mirrors. Here we describe the motivation for the LTP, the design, and a first application of the LTP to study the effect of gravity on a bent microfocusing neutron supermirror.

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1. Introduction

Recently developed Kirkpatrick–Baez (KB) neutron focusing optics allow for small neutron beams with nearly source-limited brilliance at the sample [1–4]. The key optical components are precision-bent neutron supermirrors with elliptical surfaces. Mirrors are arranged either sequentially [1–4] or in a nested arrangement [5] (Fig. 1). Focusing is essential for spatially resolved experiments, and for small-sample experiments where it is important to optimize the experimental signal-to-parasitic scattering [3]. The use of nondispersive (KB) neutron supermirror surfaces is particularly important for applications at spallation sources that are intrinsically white-beam sources and for applications to white-beam neutron reactor experiments that can efficiently use a wide neutron bandpass.

A simple mirror system capable of achieving $<100\,\mu$m-diameter focal spots has been demonstrated [1,2] and a new system capable of achieving $<25\,\mu$m-diameter spots is currently under development [6]. In order to achieve this sort of performance, deviations of the mirror figure from an ideal ellipse must be small. For example, an imperfectly figured mirror with an image distance f_2 and a figure-error blurring of ΔX_{FWHM}, must have a root-mean-square figure error $\Delta\theta_{\mathrm{RMS}}$, less than

$$\Delta\theta_{\mathrm{RMS}} < \frac{\Delta X_{\mathrm{FWHM}}}{4.7 f_2} \tag{1}$$

From Eq. (1), we estimate that an RMS figure error of $<9\,\mu$rad is needed to achieve a $25\,\mu$m spot with a 0.6 m image distance. To achieve a $<10\,\mu$m-diameter spots with the same object distance, the RMS errors must be less than $\sim 3.5\,\mu$rad.

Of course, X-ray mirror metrology and figure perfection have long exceeded the requirements for neutron mirrors. For example, X-ray mirrors with $<1\,\mu$rad are becoming common and mirrors capable of focusing to ~ 20 nm with a 0.2 m f_2 have been demonstrated ($\Delta\theta_{\mathrm{RMS}} < 21$ nrad). Compared to X-ray mirrors, however, neutron mirrors typically have long image distances and are dynamically bent to allow for flexible optimization to a particular experiment. This makes them particularly sensitive to gravity [7–9]. Indeed the effect of gravity can be much larger than the allowable neutron mirror figure tolerance.

For a simply supported beam of rectangular cross-section (Fig. 4a), the shape of the beam under the influence of gravity has been given by Howells and Lunt [7]. Including the effect of Poisson's ratio in the beam stiffness [9], the equation for the slopes becomes

$$\frac{\mathrm{d}y}{\mathrm{d}x} = m\frac{L^2 x/4 - x^3/3}{2YI} \tag{2}$$

where $m=\rho wh$ and $I=wh^3/12(1-\eta^2)$. Here L is the length of the mirror, x is the distance from the mirror center, ρ is the density of the beam, Y is Young's modulus, η is Poisson's ratio, w is the width of the beam, and h is the thickness (height) of the beam. For very realistic end-supported mirrors with dimensions of 600 mm long $\times$ 10 mm thick, the predicted rms slope errors from Eq. (2) are about $185\,\mu$rad. This is 20 times the target slope errors. It is therefore essential to measure mirrors in the orientation and support arrangement in which they will be used.

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2. System design

The overall design of the LTP optics is illustrated in Fig. 2. A laser beam is directed parallel to a precision linear-stage by a beam splitter. The linear-stage is a crossed roller bearing mechanical stage, which differs from all other previous LTPs that use air bearing translation stages. The laser beam is then deflected onto the test mirror by a pentaprism. The reflected beam from the test mirror passes back through the pentaprism into the optical head and is focused onto a linear array detector. The linear detector is set at the focal plane of the lens so the focal spot position is sensitive only to the angle of the beam after reflecting off the mirror and is insensitive to the lateral displacement of the beam in the lens aperture. The overall approach of this LTP design is to be insensitive to small angular errors in the pitch and roll orientation of the optics on the linear-stage carriage. The pentaprism deflects the probe beam by 90° and is insensitive to small pitch angle rotations about an axis perpendicular to its plane of incidence (mirror meridional focusing plane). A cylindrical lens is also inserted between the pentaprism and the mirror to focus the beam sagittally on the mirror. This removes the influence of sagittal errors—for example mirror twist—from the measurements and makes the system insensitive to small roll angle rotations of the pentaprism during translations.

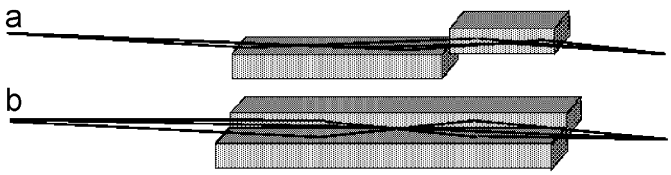

Fig. 1. (A) In a standard (sequential) Kirkpatrick–Baez geometry a primary mirror focuses in one direction and a secondary mirror focuses in an orthogonal direction. (B) In a "nested" design, some rays hit one mirror first and some rays hit the other mirror first and all the rays strike near the edge between the two focusing mirrors.

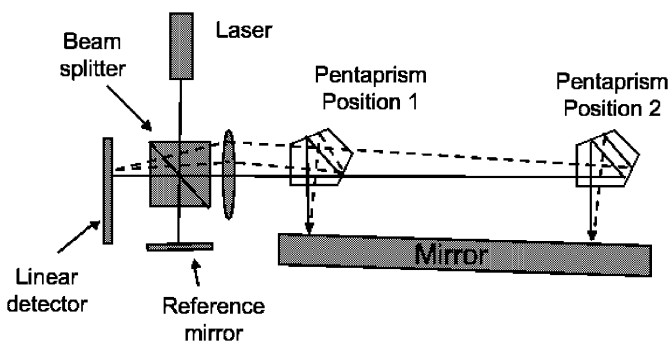

Fig. 2. Schematic of the LTP conceptual design. The laser beam is deflected onto a fixed optical axis by the beam splitter. The beam is deflected from the optical axis onto the mirror by a pentaprism which reduces the effect of rotations in the translation carriage. Sagittal errors in both the mirror and out-of-plane rotations are reduced by a cylinder lens (not shown) that is inserted between the pentaprism and the mirror being measured, with the mirror surface at the focus of the lens.

A special feature of this LTP is its ability to be rapidly configured for mirrors oriented in various reflecting geometries. Both the optical head with the linear array detector, laser and lens and the linear-stage carriage assembly with the pentaprism and cylindrical lens can rotate by 90°. The optical head has been aligned, so its optical axis does not shift laterally during rotations. Once both the optical head and the carriage assembly have been set in a new orientation, the cylindrical lens is adjusted to put its focus at the test mirror surface. The tilts of the test mirror are then adjusted to reflect the beam back on itself. This whole alignment procedure takes about 5 min. A picture of the system is shown in Fig. 3.

3. Software

The software is optimized for measuring elliptical mirrors. The measured slopes of a mirror can be fit with three options: (1) the object distance f_1 and the image distance f_2 can be assumed fixed

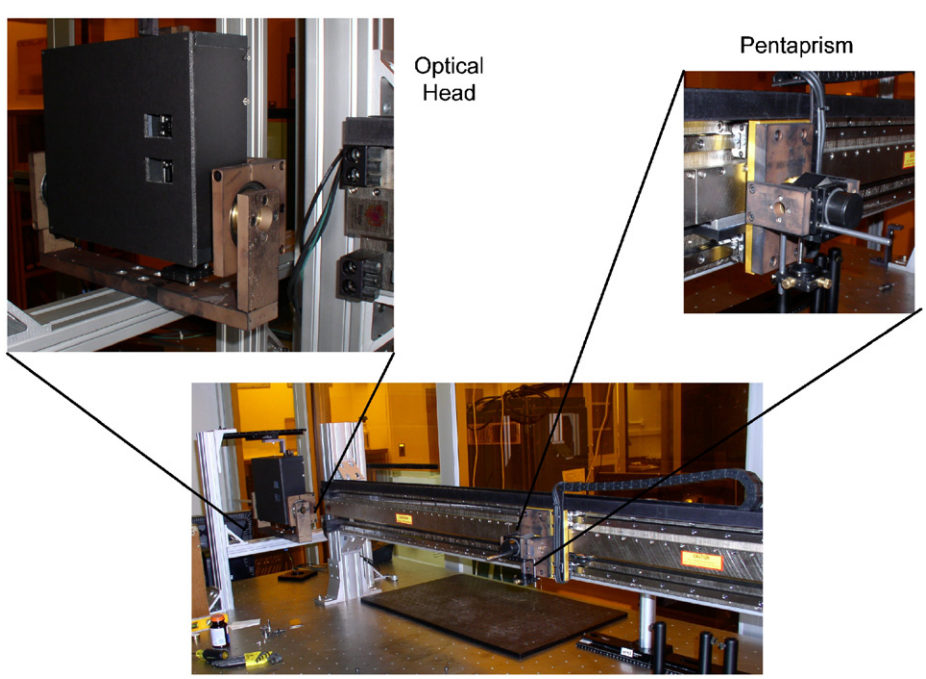

Fig. 3. The assembled LTP with the optical head assembly and the pentaprism assembly enlarged to show the rotation mechanisms. Note the adjustable cylinder lens suspended below the pentaprism.

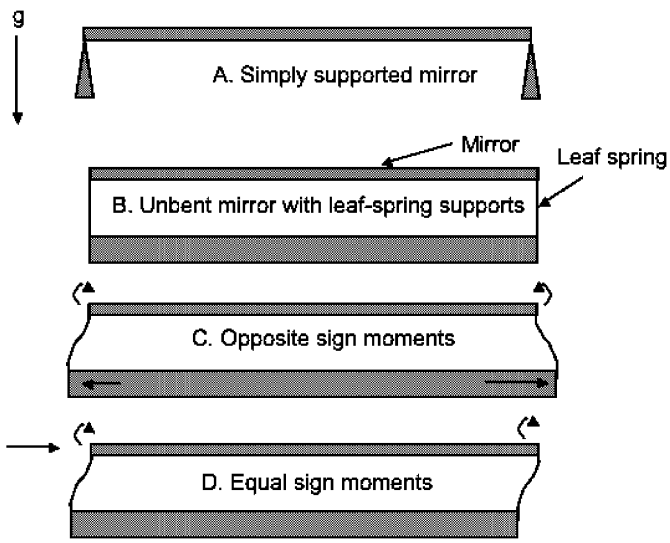

Fig. 4. (A) A simply supported mirror (beam) with the supports at the ends of the mirror. (B) An unbent mirror supported by leaf springs. (C) If the base of the leaf spring support is widened, equal magnitude by opposite sign moments are applied to the ends of the mirror. (D) If the mirror is pushed, equal moments are generated at each end of the mirror. By a combination of actions C and D, the mirror surface can be bent to approximate an ellipse.

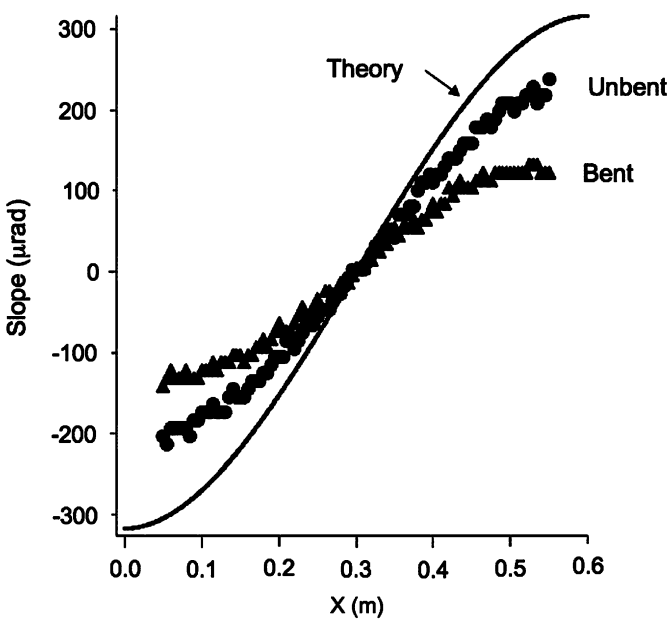

Fig. 5. (A) Theoretical slopes for a simply supported beam with the physical dimensions and properties of the measured mirror (solid line). (B) Slope difference for a bent mirror in the vertical compared to the horizontal focusing conditions. (C) Slope difference of a relaxed (not bent) mirror in the vertical compared to the horizontal focusing conditions.

with the nominal glancing angle at the center of the mirror adjustable; (2) the sum of the object and image distances can be assumed fixed with the nominal mirror glancing angle adjustable; or (3) the object, image and nominal glancing angle can all be fit for minimum RMS error.

4. Measured effect of gravity

Because the LTP can be rapidly configured to measure mirrors with surfaces oriented at all angles between parallel and perpendicular to horizontal, it is easy to experimentally measure the effect of gravity on surface figure. As an interesting first test, a mirror bent for microfocusing was measured in a horizontally deflecting configuration where gravitational effects are assumed to be negligible. The mirror uses a bending design pioneered at the advanced light source (Fig. 4) [8]. The mirror is supported on the ends with leaf springs and the shape is adjusted to approximate an ellipse by a superposition of spreading the base that supports the leaf springs and pushing on one end of the mirror (Fig. 4). The same mirror was then oriented to reflect vertically and its surface remeasured. The difference in the experimentally measured slopes (Fig. 5) was compared to the theoretical shape of an ideal simply supported beam in a gravitational field. The measured gravitational effect is roughly half of the theoretical model prediction. This difference is assumed to arise from the constraints imposed by the leaf springs on the ends of the mirrors which induce both rotational moments and tensile forces during bending [8]. To test this hypothesis, the mirror was unloaded so the mirror was in a relatively neutral bending situation. Measurements were then repeated and the measured gravitational slope changes were closer to the theoretical prediction. The small remaining difference is assumed to be due to continued constraints introduced by the supporting springs and by the weight of invar plates glued to the mirror to allow for spring attachment.

5. Conclusion

A specially designed LTP has been assembled and tested for neutron microfocusing optics. The LTP can measure long mirrors and has sufficient accuracy to calibrate mirrors for less than 25 μm focusing. The LTP can be configured to measure mirrors in the orientation in which they will be used. The ability to measure long mirrors with large angular changes will become even more important for long-wavelength neutron optics which can have much larger scattering angles.

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