Speckle-based portable device for *in-situ* metrology of X-ray mirrors at Diamond Light Source

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ABSTRACT

For modern synchrotron light sources, the push toward diffraction-limited and coherence-preserved beams demands accurate metrology on X-ray optics. Moreover, it is important to perform *in-situ* characterization and optimization of X-ray mirrors since their ultimate performance is critically dependent on the working conditions. Therefore, it is highly desirable to develop a portable metrology device, which can be easily implemented on a range of beamlines for *in-situ* metrology. An X-ray speckle-based portable device for *in-situ* metrology of synchrotron X-ray mirrors has been developed at Diamond Light Source. Ultra-high angular sensitivity is achieved by scanning the speckle generator in the X-ray beam. In addition to the compact setup and ease of implementation, a user-friendly graphical user interface has been developed to ensure that characterization and alignment of X-ray mirrors is simple and fast. The functionality and feasibility of this device is presented with representative examples.

Keywords: X-ray optics; metrology, near- field speckle, synchrotron radiation

1. INTRODUCTION

The successful exploitation of X-ray beams generated by modern synchrotron light sources, depends on a significant development of X-ray optics. X-ray mirrors are widely used at synchrotron light facilities for micro- and nano-focusing because of their achromaticity and large acceptance aperture. Moreover, X-ray active mirrors, such as bimorph and mechanically bendable mirrors, are widely used to generate either focused or defocused beams at Diamond Light Source. Although *ex-situ* metrology plays valuable role for measurement of X-ray mirrors [1-4], it is equally important to perform *in-situ c*characterization and optimisation of X-ray mirrors to achieve best performance under beamline conditions [5, 6]. In addition, accurate *in-situ* metrology is also essential to achieve diffraction-limited and coherence preserved beams [7]. Over the last two decades, several *in-situ* metrology techniques have been developed to evaluate the performance of various X-ray optics [8-12]. Among them, the speckle based technique shows great potential for wide application since it can provide ultra-high angular sensitivity with simple experimental setup [13, 14]. To apply this technique to a range of beamlines for *in-situ* characterization of X-ray mirrors, a portable *in-situ* metrology device [15-17] needs to be developed. Here, we present the development and implementation of a portable metrology device based on the X-ray speckle-based approach. We demonstrate the performance of this device by optimising the performance of a bimorph X-ray mirrors and testing alignment of an X-ray mirror.

2. DEVELOPMENT OF THE IN-SITU METROLOGY DEVICE

A schematic of the mechanical layout of the device is shown in Figure 1. The entire setup has been purposefully designed on a modular base frame for coarse alignment and ease of portability. Such a frame can readily be fitted onto virtually any beamline. The diffuser is mounted on a piezo stage for precision scanning, which in turn is mounted on an assembly of three linear stages for alignment of the diffuser with the direct or reference X-ray beam. In addition, crossed gold wires of 200µm diameter are attached to the piezo stage to permit measurement of the X-ray beam size. Coarse alignment is performed manually, and the distance between the mirror focus and the diffuser can be freely chosen so as to optimize the angular sensitivity.

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Further downstream, a CCD detector with a pixel size of 6.5µm is used to record the speckle pattern. A photodiode detector is also mounted on the detector stage to perform knife edge scan and measure the X-ray beam size. Both detectors are mounted on horizontal and vertical motorized translation stages for ease of alignment with the X-ray beam. All motorized stages are remotely controlled with an accuracy of 1µm via the Experimental Physics and Industrial Control System (EPICS) based on a Geo Brick LV system [18]. This feature is especially useful if there is a need to characterize composite optics, such as Kirkpatrick-Baez (K-B) mirrors. Experiments were conducted at the Test beamline B16 at Diamond to test the functionality of the device[19]. The photograph of the experimental assembly as installed on the beamline is shown in the bottom part of Figure 1. The portable system, consisting of the diffuser and detector, was mounted downstream of the test mirror on an optical table. The diffuser can be scanned either vertically or horizontally to retrieve the tangential slope error of the test mirrors. A standalone MATLAB GUI was used to calculate the wavefront radius of curvature by tracking the speckle displacement with cross-correlation algorithm [15].

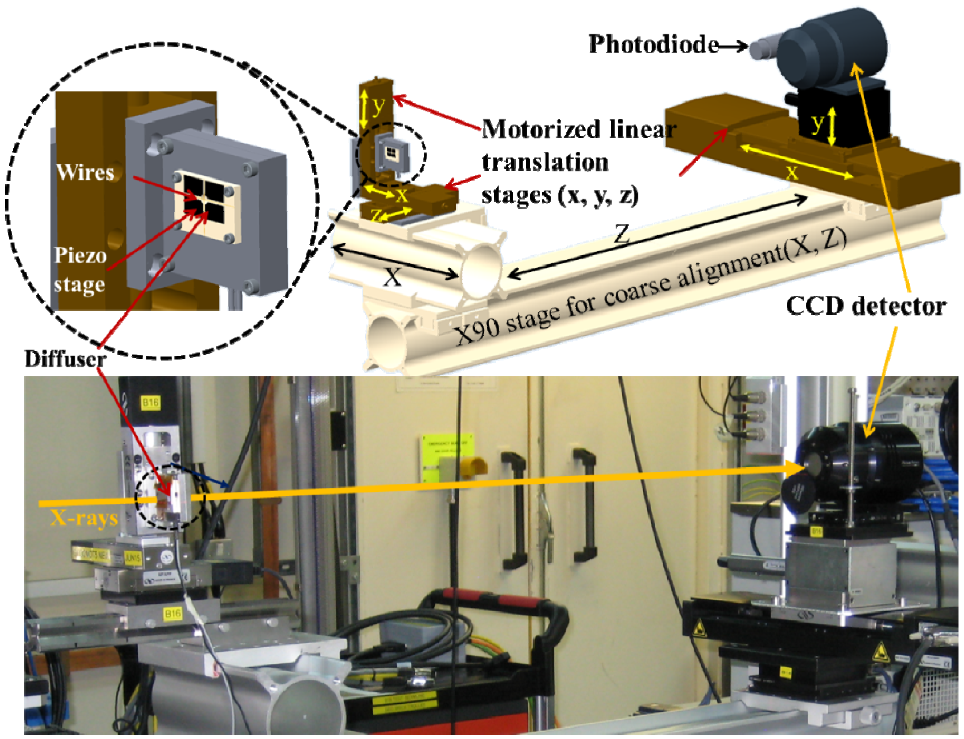

Figure 1. (Top) Schematic mechanical and optical layout of the in-situ portable device for characterisation of X-ray optics. The diffuser, gold wires, CCD detector, and photo-diode can be translated into the X-ray beam using motorized linear stages. The wavefront radius of curvature is measured by scanning the diffuser with a piezo linear stage, whereas the beam size at the focal position can be measured via a knife edge scan using the gold wires and photo-diode. (Bottom) Photograph of the portable metrology device installed on B16 beamline for the characterization of X-ray mirrors. The mirror is installed upstream of the diffuser stage and is not visible in the figure.

3. APPLICATION FOR AT-WAVELENGTH METROLOGY

3.1 Characterization of an elliptical mirror

To investigate the functionality of the device, an elliptical mirror was characterized with three methods: *in-situ* with the diffuser placed upstream and downstream respectively (portable device), and *ex-situ* using the Diamond-NOM slope profilometer [20]. Optical slope errors measured using the different techniques are shown in Figure 2. The design parameters of the mirror tested are: source to mirror distance p = 41.5 m, mirror to focus distance q = 0.1 m, and grazing incidence angle θ = 3 mrad. The polished region (70mm) of the mirror was fully illuminated with monochromatic 15keV X-rays from a double crystal monochromator (DCM). 80 images with a step size of 0.25 micron were collected to measure the tangential wavefront slope error for both *in-situ* measurements. As seen in Figure 2, the *in-situ* metrology measurements with the upstream diffuser agree well with the *ex-situ* Diamond-NOM data. It should be noted that the Diamond-NOM and the upstream diffuser measurements are directly related to errors on the mirror's surface [12], whereas the downstream configuration measures the wavefront slope errors [13]. One possible reason for the low frequency discrepancy between the downstream data and the other methods is that an ellipse was removed from slope data from the Diamond-NOM and the upstream scans, whereas only a simple linear fit was used to derive the wavefront slope error. Nevertheless, it is reassuring to see the same optical polishing errors appearing in all three sets of measurements.

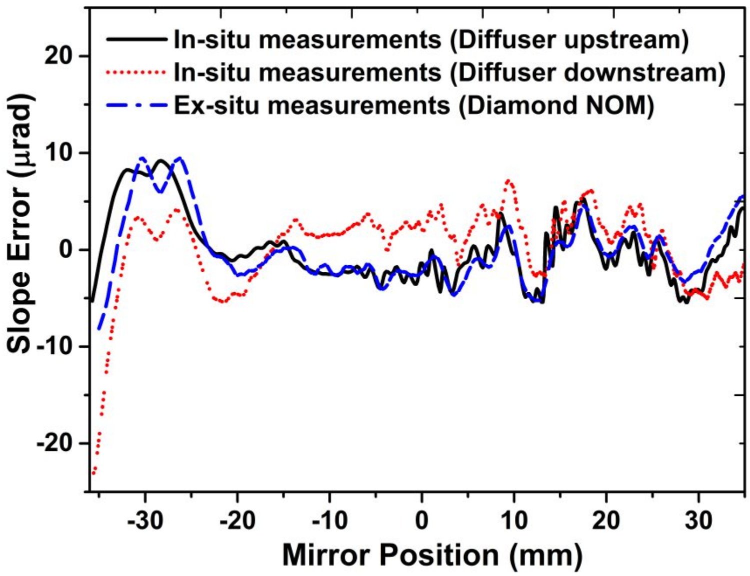

Figure 2. A comparison of the slope error of an elliptical test mirror as measured using: *in-situ* portable device with a diffuser downstream (red, dots); *in-situ* metrology using a diffuser upstream (black, solid); and ex-situ profilometry using the Diamond-NOM (blue, dash).

3.2 Optimization of a bimorph mirror

To assess the feasibility of using the portable device for optimizing an active X-ray mirror, a deformable piezo bimorph mirror with 8 electrodes was investigated. The active length of the mirror is 120 mm, and it has an elliptical shape with: p = 41.5 m, q = 0.4 m, and θ = 3 mrad. The mirror was mounted on a motorized tower in the experimental hutch of B16 at 47m from the X-ray source. Since the mirror substrate is uncoated silica, X-rays with energy of 9.2 keV were selected by a DCM for good X-ray reflectivity. A standalone MATLAB GUI was used to calculate how each of the bimorph's piezos respond to an applied voltage, the so-called piezo-response functions (PRF), by subtracting the values of wavefront slope (or inverse of radius of curvature) extracted from the j^{th} to $(j-1)^{th}$ measurement. PRF was obtained by incrementally applying 400V to each piezo electrode. Here, the PRF was determined in terms of inverse of radius of curvature for fast optimization and convergence. After deriving the PRF, the first set of optimized voltages gets automatically calculated and displayed on the GUI for user convenience. Values are also archived for further processing. To reduce the mirror's slope error, voltages generated in the first iteration were applied to relevant electrodes, and another stack of speckle images was collected to evaluate the new error of the wavefront radius of curvature for a second iteration. This process is repeated until convergence occurs. A few iterations are typically sufficient to minimize the slope error and obtain the optimal set of voltages that gives the best X-ray focus. Figure 3 shows the measured wavefront slope error after application of voltages obtained for successive iterations. Slope error was reduced from 2.3 μrad (r.m.s) to 0.2 μrad (r.m.s) in three iterations only.

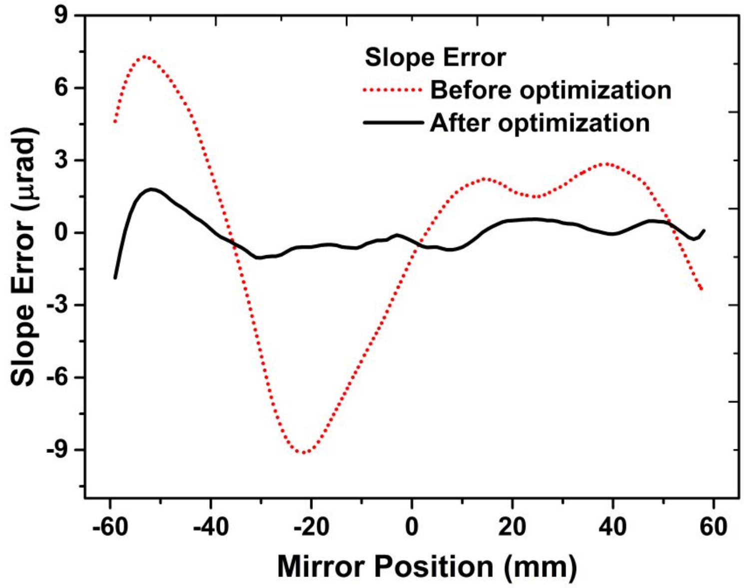

Figure 3. The optical slope error of the bimorph mirror was reduced from 2.3 μrad at zero piezo voltages (orange, dash-dot) to 0.2μrad (solid, black) at optimized voltages.

3.3 Alignment of an X-ray mirror

In addition to the characterization and optimization of X-ray mirrors, the portable device can also be used for in-situ alignment of X-ray mirrors. To demonstrate this, we used the same bimorph mirror as described in section 3.2. The portable device was placed outside the focal plane of the mirror, and the distance between the mirror and detector was set to L=1400 mm so as to increase, both the angular sensitivity and the spatial resolution of wavefront error measurement. For an elliptical focusing mirror, the wavefront error includes contributions from the upstream wavefront error, the mirror slope error and the aspherical error due to misalignment of mirror pitch angle. Therefore, the measured wavefront error will be higher if the mirror angle deviates from the designed value. This fact can be used to estimate and thus correct the misalignment of the mirror pitch angle. For this, a stack of speckle images is recorded by scanning the piezo position, and the same scan is repeated by varying the mirror angle pitch angle from 0.167° to 0.187°. The measured wavefront error ($\Delta\delta$) and the corresponding wavefront radius of curvature (R) are shown in Figure 4. The wavefront radius of curvature decreases with an increase in the pitch angle, and it indicates that the mirror focal length f=L-R moves further downstream with the increase in the mirror pitch angle. As shown in Figure 4, the minimum of the wavefront error is at the pitch angle of 0.177° (blue dotted line) rather than the design value of 0.172°. It indicates that there is an angular offset in the mirror pitch angle settings. It should be noted that the more commonly used conventional knife edge scan technique is quite time consuming as several measurements are required to find the minimum beam size along the beam path. In contrast, the measurement process with the portable device is relative fast (1-2 minutes) for each pitch angle, where both the wavefront error and the wavefront radius of curvature can be derived simultaneously. It demonstrates that the speckle-based portable device can be routinely used for fast mirror alignment.

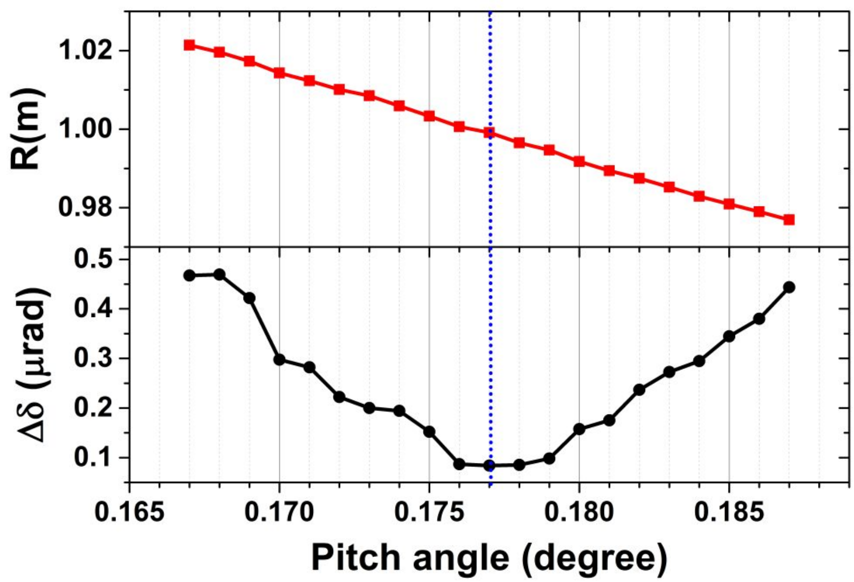

Figure 4. The measured (Top) wavefront radius of curvature (R) and (Bottom) corresponding wavefront slope error (Δδ) as function of the pitch angle, and the best alignment angle is marked with blue dotted line.

4. SUMMARY

A speckle-based portable device has been developed for *in-situ* and at-wavelength metrology of X-ray mirrors at Diamond Light Source. We demonstrate that the best focus can be achieved within a few iterations for a bimorph mirror using this device. In addition, we show that the portable device can be used for *in-situ* characterization, optimization and alignment of X-ray mirrors. This compact device can be easily implemented on a variety of operational beamlines. This fast, compact and accurate speckle-based device is expected to find wide applications for *in-situ* characterization and optimization of X-ray mirrors for synchrotron radiation community.

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