Optics Fabrication and Metrology Group
Experimental Facilities Division

Development of a Linear Stitching Interferometric System for Evaluation of Very Large X-ray Synchrotron Radiation Substrates and Mirrors

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1. Motivation

Metrology of large x-ray beamline mirrors calls for very specific tools and techniques. At synchrotron radiation facilities around the world, the long trace profiler (LTP)[1] is generally the instrument of choice, while most mirror manufacturers prefer to use a standard commercial phase-measuring interferometer (PMI), very often in a configuration where the mirror full surface height profile is measured at grazing-incidence angle. Both techniques have their own limitation. The stitching technique provides an alternative way to accurately characterize these mirrors. The concept itself is not new and has been the subject of many papers.[2-7] however, the technique has not been widely considered until recently, because it is rather difficult to implement. The stitching option is now becoming available in many commercial metrology tools, such as roughness measuring instruments. Here we focus on its application to the specific case of long-grazing-incidence x-ray mirrors, such as those used in synchrotron radiation beamlines.

If properly implemented, the technique offers the potential for providing 3D measurements of mirror surfaces with nanometer resolution. In the particular case of x-ray mirrors, obtaining a high-resolution 3D surface profile can be very useful in many instances, for example, in selecting the best reflecting stripe on a mirror surface to be used for undulator beams. The measurement data can be used for simulating and predicting mirror performance under realistic conditions. Moreover, with this technique, one can probe a range of spatial frequency wider (from submillimeter up to the size of the mirror surface) than, for example, the long trace profiler (LTP). Finally, from the manufacturing point of view, 3D measurement data can be used as feedback for computer-controlled fabrication processes to correct for possible mirror surface topography errors. In this paper, after a brief review of the stitching principle and challenges, a description of stitching system currently under development at the X-ray Optics Metrology Laboratory of the Advanced Photon Source (APS) at Argonne National Laboratory will be given. Then preliminary tests performed on two different substrates are presented and discussed.

2. Basic Principle

Figure 1 illustrates the basic principle of stitching. It consists of using a standard small-field-of-view, high-resolution interferometer to measure the surface of an oversized optic at a number of locations, resulting in overlapped subaperture measurements that cover the entire optical surface. Then these subaperture computer program to construct a full 3D Measurements are stitched together with a surface profile. Many stitching codes have been developed over the years (see Ref. 8 and 9, for example) and the basic idea is the same: the mathematical treatment consists of computing and subtracting individual tip-tilt piston functions ($f(x,y)ax+bx+c$, with a, b, and c being the stitching coefficients) from each subaperture measurement, and a criterion is set for stitching quality for overlapping subapertures. The code used in this work has been developed by one of the authors (M. Bray). As criteria for the quality of stitching, the software, in its present first version, uses the global rms of all height errors (along the vertical "z axis") over all pairs of overlapping subapertures.

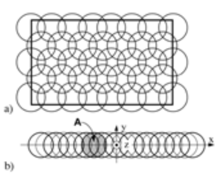

FIGURE 1: Principle of stitching, a) 2D case, b) 1D case (e.g., x-ray mirror case).

3. Challenges, Sources of Errors, and Remedies

Generally, the stitching process does not generate errors. The main challenge is to ensure that individual subaperture measurements are accurate and error free. A small perturbation in a single subaperture can propagate throughout the stitched profile resulting in a large-scale fluctuation, which in turn leads to imperfections in the overlap between individual measurements. Major sources of errors include: the interferometer noise and nonlinear effects, static errors resulting from a lack of calibration, and dynamic errors, which include thermal and mechanical errors, etc. The interferometer noise has been estimated to have a negligible effect. Nonlinear effects are dependent on the design of the interferometer, and they are the most difficult to overcome. Static and dynamic errors are not insurmountable and can be easily minimized by proper design and calibration of the measurement system.[10] The size of the overlap area (between adjacent subapertures), as well as the number of measurements, can also greatly influence the accuracy of the measurement.

3.1 Calibration

System calibration is essential in obtaining accurate measurement. Absolute calibration of interferometric systems has been the subject of numerous publications.[11-12] Stitching reveals the lack of calibration. For example, local calibration errors can propagate, thus generating errors resulting in a global curvature with local periodic errors. If stitching reveals errors, it can also help to eliminate them. For example, one can use the stitching hardware and software to acquire measurements with lateral displacement and perform some kind of "shearing interferometry." However, contrary to real shearing, noise is introduced in this process, and this must be taken into account by additional processing (ongoing work by one of the authors, M. Bray).

3.2 Environment Perturbation

Stitching can also reveal environment-related perturbations. Even with proper system calibration, thermal fluctuations can degrade the overall figure ("large-scale" errors). However, these errors can be reduced by proper design and climate control.

Abstract

Stitching interferometry, using small-aperture, high-resolution, phase-measuring interferometric systems has been investigated for quite some time now as a metrology technique to obtain surface profiles of oversized optical components and substrates. The technique offers the potential for providing 3D measurements of mirror surfaces with nanometer accuracy and resolution. The aim of this work is to apply this technique to the specific case of large, flat, grazing-incidence x-ray mirrors, such as those used in beamlines at synchrotron radiation facilities around the world. In the case of x-ray mirrors, obtaining a 3D surface profile could be particularly useful in many instances, for example, in selecting the best reflecting stripe on a mirror surface to be used for undulator beams. The measurement data can be used for simulating and predicting mirror performance under realistic conditions, etc. A fully automated system based on this technique is currently being developed at the metrology laboratory of the Advanced Photon Source at Argonne National Laboratory. Preliminary tests performed on a 460-mm-long flat float-glass substrate and on a 300-mm-long superpolished silicon substrate, were encouraging. The stitched profiles showed no obvious overlap errors, and the results agree well with those obtained using other techniques.

4. Application to Long Grazing-Incidence X-Ray Mirrors

Stitching interferometry for "standard" large components usually means generating a 2D array of measuring locations (see Figure1a). This prevents measurement errors from propagating, as each subaperture is constrained somewhat by its numerous surrounding neighbours. This is not the case for long gazing-incidence x-ray mirrors, for which the subaperture topography is reduced to 1D (Figure 1b), and a single error will propagate fully. The solution for this is to perform "double-overlap,"[10] whereby each overlap is completely constrained by an independent subaperture. In Figure 1b, the error in "A" is reduced by the large overlap. This also provides better lateral coverage of wide optics, allowing, for example, a 90-mm-wide mirror to be adequately measured with a 100 mm interferometer.

4.1 Mixed Stitching

Large-scale errors caused by, for example, thermal fluctuations can degrade the overall figure. A possible way to correct for this is to accurately measure large profile fluctuations using some other means such as an LTP or glancing-angle interferometry. Then one can use the obtained large-scale profile in conjunction with the subaperture measurements to perform a mixed stitching. The overall large-scale measurement will help in neutralizing the propagation of local errors and could lead to faster and more accurate measurement sequences.[10]

5. Measurement Setup

The stitching setup consists of a standard Phase Measuring Interferometer (a WYKO-6000) Fizeau interferometer, a long translation rail, a fringe-adjustment assembly (made of a tip-tilt and rotation platforms), and a mirror-mounting platform. The interferometer has a 150-mm-diameter aperture, and the individual pixel size, measured using a calibrated diaphragm measured at normal incidence the test beam, is 0.733 mm parallel to the main axis of the test mirror, and 0.581 mm in the transverse direction. Because the interferometer is much heavier than a typical large x-ray mirror, we chose to keep the interferometer at a fixed position and scan the mirror. The stage used to scan the mirror has sufficient accuracy and repeatability to avoid possible positional stitching errors. The various motors of the tip/tilt platform as well as the mirror rail, can be remotely actuated via a programmable motor controller and the stitching software.

6. Measurement, Results and Discussion

Preliminary tests were performed on a 460-mm-long, 100-mm-wide float-glass substrate and a 300-mm long by 40-mm-wide superpolished silicon substrate labelled SN1-2. Both substrates were measured with their optical surfaces oriented vertically, thereby minimizing deflection from gravity. The overlap between adjacent subapertures was 66% for the float-glass substrate and 64% for the silicon substrate, resulting in a double overlap for both cases. The float-glass required twelve subaperture measurements, while the silicon required seven. No calibration was performed to account for the interferometer errors. However, their contribution was expected be negligible for both measurements for the following reasons: 1) the float-glass surface contains large irregularities compared to the interferometer transmission flat, 2) due to the double overlap combined with the smaller width of the useful area (30 mm) of the silicon mirror, only a fraction of the area of interferometer transmission flat (TF) was used for the measurement. Therefore, contribution from the TF is expected to be negligible. In any case, repeatability–a primary requirement–is not affected by the lack of calibration, which only generates static errors.

Figure 2 compares residual slope error profile (left) and the corresponding 1D power density function (PSD) profile (right) with those obtained with our LTP for the float-glass substrate. The slope error profiles compare quite well, with the stitched profile showing obviously much finer details. The two PSD profiles appear to be in very good agreement up to a spatial frequency of about 10 mm^{-1} spatial frequency, then they diverge and the stitched PSD profile shows a bump centered around 0.25 mm^{-1} spatial frequency. The higher end period cutoff (Nyquist period) values are 2 mm for the LTP and 1.466 mm for stitching. The difference is not easy to interpret because the PSD calculation is sensitive to many different parameters. Further tests will be performed in the near future in order to clearly understand these discrepancies. Table 1 shows that the stitched results for the silicon substrate compare very well with those of the APS LTP, as well as those of the manufacturers (ASML Inc.).[13] Finally, for both substrates, the stitched profiles showed no obvious stitching errors as can be seen from the residual slope error plots, which are extremely effective in highlighting fine details of the surface including overlap error and polishing defects (scratches, pits, etc.). This is particularly true for the superpolished silicon for which surface irregularities are much smaller, or are too small to bury the overlap errors (see Figure 3b).

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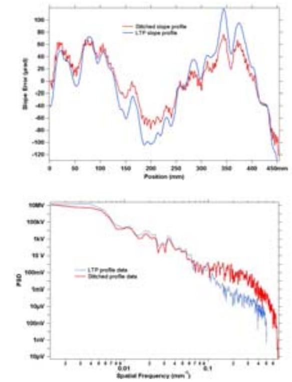

FIGURE 2: Comparison between LTP profile and 1D slice cut from the stitched profiles of a 460-mm-long float-glass substrate: left) residual slope error profile, and right) the corresponding power spectral density profile derived from height data.

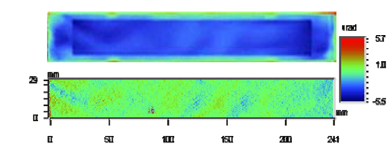

FIGURE 3: Silicon substrate results: a) height contour profile, b) residual slope contour profile over the useful area (inner rectangle in a). No evidence of overlap error observed.

	STITCHING	LTP	ASML
rms slope error (µrad)	0.64	0.66	0.62

TABLE 1. Residual slope error results for the Silicon substrate: comparison with the APS LTP and manufacturer measurements. The manufacturer (ASML Inc.) data was obtained using a 300 mm aperture interferometer.[13]

7. Conclusions

This work demonstrates that the stitching method is a promising alternative for accurate metrology of large x-ray mirrors such as those used in synchrotron radiation beamlines. A stitching system based on this technique is being developed at the Advanced Photon Source. Preliminary tests conducted on two different substrates were encouraging. Although the measurements were performed without sophisticated calibration and tightly controlled environmental conditions, the stitched profiles showed no obvious stitching errors as seen by plotting residual slope error profiles, which are extremely effective in highlighting fine details of the surface, including overlap error and polishing defects (scratches, pits, etc.). The goal is to build a fully automated system capable of characterizing state-of-the art x-ray mirror with submicroradian surface slope error.

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