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Development of a high-performance gantry system for a new generation of optical slope measuring profilers

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ABSTRACT

A new high-performance metrology gantry system has been developed within the scope of collaborative efforts of optics groups at the US Department of Energy synchrotron radiation facilities as well as the BESSY-II synchrotron at the Helmholtz Zentrum Berlin (Germany) and the participation of industrial vendors of x-ray optics and metrology instrumentation directed to create a new generation of optical slope measuring systems (OSMS) [1]. The slope measurement accuracy of the OSMS is expected to be <50 nrad, which is strongly required for the current and future metrology of x-ray optics for the next generation of light sources.

The fabricated system was installed and commissioned (December 2012) at the Advanced Photon Source (APS) at Argonne National Laboratory to replace the aging APS Long Trace Profiler (APS LTP-II). Preliminary tests were conducted (in January and May 2012) using the optical system configuration of the Nanometer Optical Component Measuring Machine (NOM) developed at Helmholtz Zentrum Berlin (HZB)/BESSY-II. With a flat Si mirror that is 350 mm long and has 200 nrad rms nominal slope error over a useful length of 300 mm, the system provides a repeatability of about 53 nrad. This value corresponds to the design performance of 50 nrad rms accuracy for inspection of ultra-precise flat optics.

1. Introduction

In this article, we discuss the results of preliminary performance tests of a new metrology gantry system developed by a collaboration of optics groups at the US Department of Energy synchrotron radiation facilities—Argonne National Laboratory/Advanced Photon Source (ANL/APS), Lawrence Berkeley National Laboratory/Advanced Light Source (LBNL/ALS), and Brookhaven National Laboratory/National Synchrotron Light Source-II (BNL/NSLS-II)—as well as the BESSY-II synchrotron at Helmholtz Zentrum Berlin (Germany) with the participation of industrial vendors of x-ray optics and metrology instrumentation. The collaborative efforts are directed to create a new generation of optical slope measuring systems (OSMS) [1] with a desired accuracy of a surface slope measurement of <50 nrad (absolute) when measuring flat as well as highly curved x-ray optics. This level of accuracy is necessary for current and future metrology of x-ray optics for the next generation of light sources [2].

The fabricated gantry system was installed and commissioned at the Advanced Photon Source at Argonne National Laboratory to replace the aging APS Long Trace Profiler (APS LTP-II) [3]. Preliminary tests were carried out in January and May 2012, using the optical arrangement of the Nanometer Optical Component Measuring Machine (NOM) [4–7]. Measurements of a flat Si mirror showed a high repeatability of about 53 nrad (see also Ref. [8] in the present issue). This value is nearly the desired performance of 50 nrad rms accuracy for inspection of ultra-precise optics.

Non-contact optical profilers are the instruments of choice for measuring the figure and finish of synchrotron radiation mirrors. Since the late 1980s, the long trace profiler has been the de facto standard for surface figure measurement on the large radius spheres, flats, and aspheres used in synchrotron radiation (SR) beamlines [9–12]. The original LTP I at Brookhaven National

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Laboratory was designed to measure cylindrical aspheres, where slope errors of 10 μrad were considered to be state-of-the-art. Advances in synchrotron machine technology over the ensuing decades have resulted in vast improvements in SR beam quality, necessitating similar improvements in the accuracy of the surface profiling instruments. The new generation machines, such as the LCLS, the NSLS-II, and the European XFEL, will produce x-ray beams with a high degree of coherence. Moreover, existing third-generation sources such as the APS, ALS, ESRF, and SPring-8 are all currently being upgraded to produce beams with more spatially coherent flux. In order to preserve the intrinsic quality of an x-ray beam, mirrors will need to have surface figure errors that do not exceed 1 nm over spatial periods of several hundred millimeters [2]. This translates into slope measurement error levels of less than 100 nrad.

To meet the challenge of measuring mirrors with slope errors at the 50 nrad level, several groups have developed metrology instrumentation with advanced capabilities. The best performing slope measuring profilers at synchrotron facilities, such as the NOM at Helmholtz Zentrum Berlin (HZB)/BESSY-II (Germany) [4–7] and at the Diamond Light Source (UK) [13], as well as long trace profilers at SPring-8 (Japan) [14], ESRF [15,16], SOLEIL (France) [17,18], and the Advanced Light Source [19–21], come close to the required precision. As a result, an accuracy level of better than 60 nrad in measurements with close to flat optics has been achieved. However, extending this accuracy to measurements with steeply curved optics is limited by systematic effects, inherent to the optical slope sensors in use. In practice, using different methods developed so far for suppression and accounting of error in slope measurements, an accuracy on the level of 0.1–0.4 μrad, depending on the curvature of the surface under test, can be achieved [18,21–26]. A comprehensive review of the errors of slope measurements can be found in Ref. [27].

There are three possible ways to overcome the systematic error limitations. These are the sophisticated ex situ and in situ calibration of a profiler [25,26,28], the optimization of measurement procedures [18,21,24], and the use of novel optical slope measuring sensors [29–31]. The collaborative work on a next-generation OSMS [1] assumes research and development in all these directions. Therefore, the prototype OSMS gantry system has been designed to encompass the required R&D, providing a smooth translation among different kinds of optical sensors, including a large field of view sensor (e.g., interferometer) with a significantly increased total mass (up to 50 kg). This is in contrast to the standard NOM gantry system (< 20 kg) that is designed to solely translate relatively low mass passive optics (pentaprism, aperture, etc.), whereas the optical sensors (an autocollimator and an LTP pencil-beam interferometer optical sensor) are mounted stationary.

The basic approach to the design of the OSMS gantry system is presented in Ref. [1]. The particular realization of the OSMS gantry system prototype, installed at APS, Argonne National Laboratory is presented in this paper. The mechanical gantry system design is discussed in Section 2. The EPICS-based control system is presented in Section 3. The environmental enclosure is detailed in Section 4. Results from preliminary performance tests are presented in Section 5 and in Ref. [8].

2. The gantry system

The gantry system was designed and built in collaboration with ALIO Industries [32]. Fig. 1 shows the design layout of the system.

The ALIO design (Fig. 1) includes three axes' motion, two of which are orthogonal, high-precision metrology axes. One of the two motions (along the X-axis) provides 1.5 m translation of the optics board carriage, the other motion (along the Y-axis) is for the lateral scanning of the test mirror surface. The third separate motion (along the X'- axis, Fig. 1), parallel to the primary 1.5 m axis, provides X-axis tracking cable translation. This is the main distinguishing feature of the OSMS gantry system from the NOM. The second parallel translation provides the opportunity to use an optical sensor with reasonably stiff and short cables such as those of a large field of view interferometer [29].

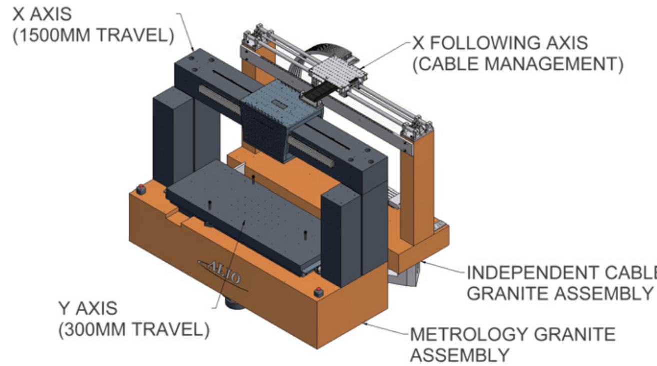

Fig. 1. System layout showing primary metrology axes (X and Y), cable tracking axis (X'), and the system granite structures.

Table 1
Maximum angular error over the full travel of the X and Y axes.

Axis	X	Y
Pitch	± 2.6″	± 0.3″
Yaw	± 0.5″	± 0.3″
Roll (dual flatness)	± 1.25″	± 0.5″

The system's frame, optical table, and mirror platform are made of granite with nearly 12,000 kg of high precision, low expansion coefficient stone resting on a three-point kinematic mount with vertical adjustment machine tool pads. The top optical carriage (X-axis) is an extremely stiff carriage riding on porous media air bearings with a dual motor drive where the motor force acts along the center of gravity to reduce the Abbe error. A high accuracy Zerodur encoder scale allows for high precision laser mapping of the carriage and sub-25 nm bi-directional repeatability. The lower mirror translation system (Y-motion) is based on ALIO's patent-pending planar air bearing design. This design allows for sub arc-sec pitch and roll and is driven via Y–Y' motion commands that also permit yaw control well below 0.5'' (∼2.4 μrad).

Table 1 summarizes the angular error over the full travel range of the X and Y axes measured (see Figs. 2 and 3) with a laser interferometer per ASME B5.54-2005. The third additional X' translation system is used to fully isolate all metrology motions from the optical sensor specific cables. This cable translation system has its own granite structure and frame for dampening of cable track vibrations, plus a large cable loop bringing all cables to a carriage that follows along the metrology head axis. The motor and encoder cables for the metrology head have a flexible cable loop from the cable drive to the metrology head. The cable translation system also has a large mounting area where additional instrumentation can be placed.

The gantry system is driven by an industry-leading (Delta Tau Data System Inc. [33]) high-performance controller with precision (Trust Automation [34]) linear amplifiers. The controller is compatible with the Experimental Physics and Industrial Control System (EPICS) [35].