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Advance in a nano-accuracy surface profiler with an extended-angle test range

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ABSTRACT

An advanced design of a nano-accuracy surface profiler (NSP) is introduced wherein we combined a scanning optical head with non-tilted reference system to facilitate measurements over an extended range of angles. The lateral motion of the beam during testing of a strongly curved mirror induces a systematic error. For a pencil-beam scanning profiler, the arm with varying optical-path lengths should be non-tilted so to eliminate the beam's lateral motion, and the arm for testing larger angles should be short and fixed so to reduce the beam's lateral motion. Our new scheme of having a non-tilted reference system offers an effective, simple, and convenient solution. A beam spot of 0.5–1 mm is used for higher spatial frequency tests in surface-figure measurements. Some preliminary studies and test are demonstrated.

1. Introduction

The mirrors used for new-generation synchrotron beamlines, X-ray free electron lasers (XFEL), extreme ultra-violet lithography (EUVL), and astronomy require large-scale nano-accurate optics. For example, to focus a synchrotron (SR) beam to a nanometer-sized beam spot and to assure its coherent preservation, the mirror should possess nanometer and nano-radian accuracy. According to simple geometric-optics calculations, if there is 0.1 μrad slope error at a point on focusing surface, it will deflect a single ray by 4 nm at a 20 mm focal distance, viz., a large compaction to a 1 nm spot.

The long trace profiler (LTP) was the first pencil-beam scanning profile developed for synchrotron optics [1]. It has undergone significant improvements and modifications [2] over 25 years, yielding the commercial LTP II and LTP V, the penta-prism LTP [3], the in-situ LTP [4], the multiple functions LTP [5], the vertical scanning LTP [6], and so on.

The Nano-Optic-Measuring Machine (NOM) is the world's most accurate profiler. It incorporates a special commercial autocollimator and an LTP optical head with a scanning penta-prism system to measure long-radius optics [7,8]. In order to have suitable spatial-frequency range of the measurement, the large aperture of the autocollimator is replaced by a 2–4 mm pinhole setting near the mirror being tested. The demonstrated uncertainty of the NOM in these measurements was less than 0.1 μrad; a scanning penta-prism mode precludes the need to use a reference beam to correct the slide-pitch error. Similar and improved Diamond-NOM and Alba-NOM also have been developed [9,10].

Many advantages of pencil-beam scanning methods have made them a promising metrology approach for making nano-accuracy surface profilers: non-contact tests, absolute measurement without the need for using a large reference, high accuracy, possibility of measuring large-dimension optics and aspheric optics at moderate cost, and no requirement for adjusting working distance because a collimated beam is used. These advantages keep this method as one of the most important solutions for future optical metrology, even though it has the disadvantage of being only a one-dimension measurement with low test speeds. However, the sub-aperture interferometer stitching method is beginning to be employed with LTP [11,12]. Relative-angle-determinable stitching interferometry (RADSI) also was developed to measure steeply curved X-ray mirrors with nanometer accuracy [13].

2. Problems in attaining nano-accuracy with an extended-angle test range

Testing strongly curved surfaces in highly problematic for pencil-beam scanning profilers, as it is for most optical measuring techniques. In this case, nano-accuracy measurements are hard to acquire in large part due to the insufficient quality of the profiler's optical system.

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Let us analyze the variation in the beam's position in the optical system during the measurements. We use as an example a spherical mirror under test (MUT), scanned by the scanning optical head of the LTP II [14]. The sample beam (solid line, Fig. 1a) measures the slope of the MUT, and the reference beam (dashed line) measures the air-bearing pitch error. To avoid overlapping the sample- and reference-beam on the CCD, the latter is tilted to move the spot to one end of the detector, or in vertical direction when applying 2D CCD. During the scan, both the sample and reference beams have lateral motions (BLMs) over the optical components inside the optical head, depicted as solid and dashed-shadow areas, which will pick up large local-phase shift errors that show up as errors in surface slope. They are produced by errors in surface figuring, inhomogeneity of optical components, system aberrations and system-alignment errors. However, the lateral motion of the sample beam is an unavoidable condition in testing the slope of curved mirrors, but we effectively can lower the magnitude of the sample's BLMs by adopting a novel scheme.

In contrast, the penta-prism scanning mode (employing fixed LTP optical head or autocollimator) has a much larger BLM than does the scanning optical head (Fig. 1b), so we do not recommend using it for measuring large slope optics.

We took comparative measurements of a tilted reference and a non-tilted reference on the reference arm of the LTP III over a 900-mm long scan. The tilting angle was 1.5 mrad that produces a 3 mm lateral motion across the PBS. We recorded an absolute difference of about $\pm 5\ \mu$rad $(P-V)$, indicating that this is a serious slope error for a nano-radian surface profiler.

As the tilt angle of a strongly curved mirror increases, the systematic error of the profiler becomes much more severe. Also, if the reference-beam spot is displaced away from the system's center, even in the case wherein a second linear CCD or 2D CCD is used, it still will generate considerable BLM in the vertical direction at the level of a 2–3 mrad angle. This method is also not suitable for a system with nano-accuracy. Our findings from several tests indicate that the magnitude of the absolute slope error caused by BLM might exceed 1 μrad rms.

An error simulation analysis using a 20 mm sinusoidal wave-front error indicates that a 1 nm wave-front error of the refraction or reflection surface figure could produce a 0.2- or 0.6-μrad slope error, and a high-quality prism with $\delta n = 5e-7$ index error could have 0.2 μrad residual slope error [2]. Most non-contact optical profilers that employ optical systems for measuring angle variation at the nano-accuracy level will face these difficulties if there is BLM. Examples of such systems are the optical head of the LTP, and the autocollimator of the NOM. Accordingly, we are presently applying the best-quality glass Grade H5 and $\lambda/100$ figured surfaces for the nano-accuracy profiler.

3. Schematic design solution: scanning optical head combined with non-tilted reference beam

As described above, there is beam lateral motion (BLM) in the optical system during the beam scan on a curved surface that generates a significant slope error. If this error cannot be removed or greatly decreased, nano-accuracy will be difficult to reach in the range of large-slope tests.

A good schematic design of the profiler can very effectively reduce BLM. The first step is to use as few optical components as possible so to eliminate unnecessary BLM error. The second step is to a design novel optical system for the profiler to minimize BLM. Adopting the mode of a scanning optical-head combined with non-tilted reference beam is an effective solution [2,14–16] for a nano-accuracy surface profiler in an extended range of slope testing.

One satisfactory non-tilted reference method to eliminate the BLM is to use an independent second optical head as reference beam arm. In this case the reference beam is on another CCD so the beam spot overlapping problem can be eliminated.

The first advantage of applying a scanning optical-head lies in creating an opportunity to use a short fixed working-distance for the sample beam. In this way, the sample beam's BLM can be reduced significantly to ± 1 mm (50 mm working distance) in comparison with ± 20 mm BLM in the scanning penta-prism

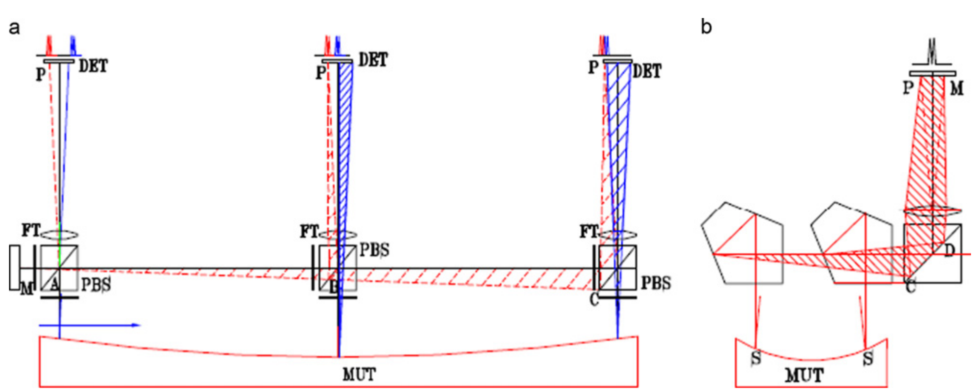

Fig. 1. Beam lateral motion during the scan: (a) sample and reference beams' lateral motion in scan optical head mode; (b) beams' lateral motion on a scan in the penta-prism mode. FT—lens, PBS—polarization beam splitter, DET—detector, MUT—mirror under test.

Table 1
Comparison of three scanning modes.

Scan mode	Working distance (mm)	BLM (mm)/test angle	Test angle (mrad)	Extra optics	Comment
Scan OH+non-tilted Ref. (NSP)	Sample: 50 (fixed) Ref.: 100–1100	Sample: $\pm 0.5/\pm 5$ mrad $\pm 1/\pm 10$ mrad Ref.: 0	± 10	N/A	Larger test angle+high accuracy
Scan OH+tilted Ref. (LTP II)	Sample: 50 (fixed) Ref.: 100–1100	Sample: $\pm 0.5/\pm 5$ mrad Ref.: $\pm 10/\pm 5$ mrad	± 5	N/A	Suitable for plane and near-plane mirror tests
Scan penta-prism (PPLTP, NOM)	Sample: 300–1300	Sample: $\pm 10/\pm 5$ mrad	± 5	Penta-prism/ mirror	Suitable for plane and near-plane mirror tests