Surface gradient integrated profiler for X-ray and EUV optics

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Abstract

A new ultraprecise profiler has been developed to measure, for example, asymmetric and aspheric profiles. The principle of our measuring method is that the normal vector at each point on the surface is determined by making the incident light beam on the mirror surface and the reflected beam at that point coincident. The gradient at each point is calculated from the normal vector, and the surface profile is then obtained by integrating the gradients. The measuring instrument was designed in accordance with the above principle. In the design, four ultraprecise goniometers were applied to adjust the light axis for normal vector measurement. The angle-positioning resolution and accuracy of each goniometer are, respectively, 0.018 and 0.2 μrad. Thus, in the measuring instrument, the most important factor is the accuracy of the normal vectors measured by the goniometers. Therefore, the rotating angle-positioning errors were measured and calibrated. An elliptical profile mirror for nanometer hard-X-ray focusing was measured, and compared with the measured profile using a stitching interferometer. The absolute measurement accuracy of approximately 5 nm (peak-to-valley) was achieved. Then the measurements of 1000-mm-long flat, spherical and parabolic mirrors were demonstrated. The surface profiles of the mirrors were obtained by integrating the interpolated gradient.

Keywords: Synchrotron radiation optics; EUV; Surface figuring; Slope error; Normal vector; Goniometers; Asymmetric aspheric figure

1. Introduction

In the presently designed ultrahigh precision profiler, the principle of our measurement method is that the normal vectors at each point on the surface are determined by making the incident light beam on the mirror surface and the reflected beam at that point coincident [1,2]. The gradients at each point are calculated from the normal vector, and the surface profile is then obtained by integrating the gradients. By determining the normal vectors to an accuracy of 0.1 μrad, the surface profile can be calculated to nanometer accuracy. The features of the present measuring method are as follows. (1) It is not necessary to reference the surface, (2) any shape of surface can be measured and (3) it does not have a limited aperture size. This measuring method has been developed and evaluated and is called the surface gradient integrated profiler (SGIP).

Our measurement instrument consists of an optical system, a specimen holder and an ultraprecise mover control system for seeking the normal vector on the mirror. It is installed in a clean room that has precisely controlled temperature and humidity. As a result, a high accuracy of normal vector measurement is achieved.

2. Principle of measuring method

The principle of the measuring method in the present study is as follows [1]. The position of the light source and the direction of the reflected beam at that point are adjusted to make them coincide. The beam vector thus becomes the same as the normal vector at the specified point on the mirror, as shown in Fig. 1(right). By
conventional measuring methods, ensuring that the incident light beam and the reflected beam coincide at every measuring point on the mirror, a common path can be obtained. By determining the normal vector to an accuracy of 0.1 μrad, the surface profile can be calculated with nanometer accuracy. The gradient of the incident point of the light beam can be attained from this normal vector. By repeating this operation, the gradients of each point on the surface of the mirror can be obtained. The \(x\) and \(z\) components of the surface gradient at a specified point on the mirror surface are measured. To obtain the surface profile by integration, it is necessary to interpolate the measured data, and to know the gradient at an arbitrary point. Interpolation of the measuring accuracy of the surface profile depends on the accuracy of interpolation of the data. In the present study, we use the least-squares method with a spline function to interpolate the data. A spline function is able to interpolate the curve of an arbitrary shape. The surface profile of the mirror is obtained by integrating the interpolated gradients.

3. Measuring instrument

Fig. 1(left) shows a photograph of the experimental instrument [1]. It shows the stages for the optical system and the specimen holder. The guides for these moving stages are constructed of double V grooves, and are designed to assure rigidity. Thus, the amount of pitching and yawing can be easily limited to within 0.1 μrad over a movement of 80 mm length. The rotating mechanism of the four goniometers can be driven not only by a wormgear but also by piezoactuators for easy setting of the angle with a resolution of 0.1 μrad. These goniostages make it possible to attain an angular resolution of 0.018 μrad by electrically dividing one pulse of the rotary encoder. The angle-positioning accuracy of the goniometers was calibrated [2]. We constructed a small shelter to ensure insulation from external temperature fluctuations using 100-mm-thick styrol foam in a temperature-controlled room, which itself was designed to limit temperature changes to within \(±0.3^\circ\text{C}/\text{day}\). The temperature change in the shelter was within \(±0.01^\circ\text{C}/\text{h}\).

All of the mirrors were measured facing sideways; the laser beam was horizontally irradiated on to the mirror surface. The mirrors were scanned along their longitudinal axis over their length. The sampling distance could be selected. The mounts for a flat mirror had a rod and a ball bearing spaced by \(\frac{L}{2}\) in the longitudinal direction and centered on the mirror transverse axis. Here, \(L\) is the length of the mirror. The mount for a round mirror consisted of two rods oriented 45° from the direction of gravitational force. Currently, the use of a Teflon sheet with pinholes for vacuum chucking is explored for realizing minimum deflection of the mirror. The deflection due to the mounting of the mirror is lower when measured with the mirror facing sideways than with the mirror facing upwards.

4. Evaluation of performance

Incremental feed tests of the four goniometers were performed with a 0.1 μrad positioning angle. The long-term stability during a 1 h period of the whole system was good enough to measure the normal vector with 0.1 μrad accuracy. Also, the measurement reproducibility of normal vector measurement and measurement on the same measurement line after rotating the mirror by 0.1 μrad around the horizontal axis were tested. In both the tests, the measured value of the normal vector was in good agreement, within \(±0.2\) μrad, using the \(\theta\) and \(\alpha\)
goniometers. The two-dimensional surface profiles on the centerlines horizontal and vertical to the SiC flat mirror (30 mm in diameter, 10 mm in thickness) were measured and compared with those obtained by the interferometric method. The present measurement results and interferometric measurement results were also in good agreement of within 2 nm. Finally, the elliptically designed profile mirror for enabling nanometer hard-X-ray focusing was measured and the results were compared with those obtained by relative angle determinable stitching interferometry (RADSI) [3,4]. The results were coincident within 5 nm (peak-to-valley) [1].

5. Demonstration of measurements of 1000-mm-long flat, spherical and parabolic mirrors

Fig. 2 shows the setup for the 1000-mm-long flat and parabolic mirrors. After the setup was completed, the mirror was left for 1 day to reach temperature equilibrium before measurements were initiated. Each mirror was scanned along a line centered on the transverse axis. Five scans were performed and the data were averaged to obtain the final mirror slope profile. Table 1 summarizes the measurement performance for each mirror, of the technique described above.

Fig. 3 shows the results of normal vector measurement for differently shaped mirrors. Fig. 3(a) shows the measurement slope profile of the 1000-mm-long flat mirror and the difference between first and second measurements. Fig. 3(b) shows the measurement results for the concave mirror with the 300 mm radius of curvature. The normal vector measurement was performed along the centerline in the horizontal direction of the mirror. Then, interpolated measured data and the shape were obtained by numerical integration. The shape was compared with the ideal spherical profile. Fig. 3(c) shows the measurement result for the parabolic mirror [5,6]. Then, interpolated measured data and the shape were obtained by numerical integration.

6. Conclusion

We developed the SGIP to measure the surface profiles of large X-ray and EUV mirrors with high spatial resolution. The developed measuring instrument was evaluated for the measurement accuracy of the surface profiles of flat, elliptical and spherical mirrors. An absolute measurement accuracy of approximately 5 nm (peak-to-valley) was achieved using an instrument with a cylindrical surface having the same curvature as the elliptically designed profile to enable nanofocusing. A steep shape, such as a radius of curvature of 300 mm and a coaxial off-axis parabolic mirror can be measured without any problems. The measurement repeatability for the 1000-mm-long flat mirror was 0.28 μrad RMS. However, the accuracy of the measured data has not been evaluated. It must be evaluated with a different surface-measuring technique such as phase shift interferometry [7].
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Fig. 3. Results of the slope measurements for 1000 mm-long-flat, the spherical and parabolic mirrors: (a) is the 1000-mm-long flat mirror, (b) is the concave mirror and (c) is the parabolic mirror, respectively.