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# Simulation-based systematic error compensation for nanoprofiler using normal vector tracing method

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ABSTRACT

We have developed a nanoprofiler that relies on the use of the normal vector. Our aim was to enable the measurement of the profile of free-form surfaces with high precision. Since the nanoprofiler does not use a reference surface, it should be capable of measuring free-form surfaces with a high degree of accuracy. Repeatability at the sub-nanometer level has been achieved. In this study, with a goal of reducing and evaluating the related uncertainty, we set out to estimate the degree of systematic error. We investigated the effect of the systematic error on the measurement results by computer simulation. Then, by comparing the measured results with those of the simulation, we estimated the systematic error.

## 1. Introduction

With the development of facilities and devices that use synchrotron radiation (SR), highly coherent X-ray light sources (for example, X-ray free-electron laser sources such as the SPring-8 Angstrom Compact Free-Electron Laser (SACLA)) are now available. To develop a practical application using such a light source, there is a demand for highly accurate aspherical mirrors with which focusing at the nanometer scale can be realized. In industry, highly accurate aspherical mirrors are used in the optical projection systems used in demanding next-generation lithography applications that use extreme ultraviolet or soft (13.5-nm) X-ray light sources. Consumer products such as digital cameras and projectors now employ free-form optical elements with radii of curvature of less than 10 mm [1,2].

The fabrication of such optical elements involves highly precise measurement. We set out to develop a measuring method that can be applied to next-generation high-accuracy aspherical or free-form optical elements. Currently, the most commonly used measuring methods involve the use of an interferometer and coordinate measuring machine (CMM). However, interferometers depend on the accuracy of an external optical reference, and CMMs are severely limited by the measurement angles at which accurate results can be obtained [3,4]. Novel methods such as stitching interferometry [5] and deflectometry [6] are capable of measuring aspherical surfaces but are not sufficiently accurate. Therefore, we developed a new type of nanoprofiler that can trace the normal vector of a mirror's surface. The principle of our measuring method is as follows.

By matching the incident light and reflected light with the mirror surface, the normal vector for each measured

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point of the mirror is obtained. The nanoprofiler consists of an optical head motion unit and a sample motion unit. The optical head motion unit controls the direction of the incident light by moving the optical head. Meanwhile, the sample motion unit controls the direction of the reflected light by moving the sample. The optical head motion unit incorporates two pairs of goniometers and a linear stage, while the sample motion unit has two pairs of goniometers. Using these five stages, it is possible to match the incident and reflected light. The normal vectors and their coordinates are acquired and, using this information, the three-dimensional shape of a mirror can be calculated by applying a reconstruction algorithm [7]. The profiler relies on the straightness of the laser light, rather than the accuracy of a reference surface. Therefore, the profiles of free-from surfaces can be captured using the proposed method. The profiler can determine the shape of a high-precision mirror with repeatability on the sub-nanometer order [7].

To measure the profile of an absolute surface, however, it is necessary to know the degree of accuracy as well as the repeatability of the surface figure measurement. The accuracy of the measurement is partially dominated by systematic errors. Therefore, through the application of a numerical simulation of these errors, we investigated their effect on the surface measurements. Assembly errors for six degrees of freedom (3-axis rotation and 3-axis translation) arise in the assembly of the sample stage, quadrant photodiode (QPD), and laser. The effects of each error on the surface measurement were determined. The results obtained from the measurement were attempted to be corrected, using the results obtained by an assembly error simulation.

In this case, if the random error is too large, the accuracy of the correction is expected to worsen. Therefore, concave spherical mirrors with a 400-mm radius of curvature, for which the accidental error factor is the smallest, were used. The nanoprofiler measures the general shape by applying 5-axis stage control. However, when measuring a concave spherical mirror for which $R = 400$ mm, only the rotation stages of the two axes are used. Therefore, problems related to the accuracy of the stage and the dynamic stiffness of the device are mostly suppressed.

Simultaneously with this correction, it is possible to estimate the degree of the assembly errors. Although the error amounts as estimated at this point consist of multiple assembly errors, they are indicative of the error for the overall apparatus. The error amounts assumed when the apparatus is assembled are as follows. Mounting errors for the sample are assumed to be on the order of 1 μm in the translational direction. Each stage is assembled with an allowable assembly error of 1 μm. The optical path length error is unknown. Using the ideal shape data of the sample during the experiment, the optical path length can be adjusted. (The optical path length error is related to the shape error of the sample.) The overall angle error is assumed to be suppressed to several μrad. The estimated errors, other than the optical path length direction of the error, do not deviate significantly from the assumptions. The optical path length error cannot currently be estimated due to the influence of the shape error of the sample. However, it is possible to roughly calibrate the surface figure measurement from the systematic errors obtained by simulation.

## 2. Nanoprofiler

Fig. 1 illustrates the principle on which the proposed profiler is based. It relies on the straightness of laser light and the high accuracy of the rotational goniometers [8,9]. Our proposed measuring device consists of an optical head motion unit and a sample motion unit. The optical head motion unit incorporates two goniometers (one rotating around the $\theta$-axis and the other around the $\varphi$-axis), one linear motion stage (moving along the $y$-axis), and a sample motion unit with two goniometers (one rotating

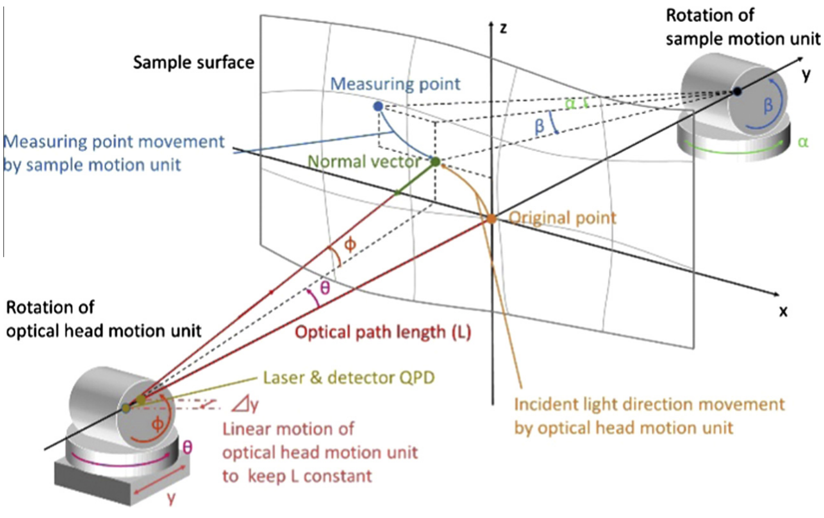

**Fig. 1.** Principle of profile measurement system.