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High-accuracy three-dimensional aspheric mirror measurement with nanoprofiler based on normal vector tracing method

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A R T I C L E I N F O

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A B S T R A C T

The demand for high-accuracy aspheric optical elements has increased significantly in recent years. The surface shapes of such optical elements must be measured with 1 nm Peak-to-Valley(PV) accuracy; however, it is difficult to achieve 1 nm PV accuracy with conventional methods. In this research, we developed a nanoprofiler based on the normal vector tracing method that can achieve the required accuracy. An aspheric mirror was measured by using the nanoprofiler, and repeatable, sub-nanometer measurements were achieved. Furthermore, we compared our nanoprofiler results with those of a Fizeau interferometer and found that the difference was within the systematic error.

1. Introduction

In recent years, the demand for optical elements of various shapes has increased. High-precision free-form optical elements will enable further advancements in scientific knowledge in area of astronomy, biology and so on, as well as the production of high-performance (lightweight, compact, and multifunctional) industrial products. For extreme ultraviolet lithography (EUVL), X-ray free electron lasers (XFELs), and third-generation synchrotron radiation facilities, optical elements such as lenses and high-precision mirrors with a variety of shapes are required. Aspheric optical elements are also necessary in digital video equipment, such as medical imaging devices, space-borne imagers, high-quality cameras, and projectors.

A peak-to-valley (PV) shape error of at most 1 nm is required for lenses with asphericities of 15 μm or more, such as the next-generation high-precision mirrors used in XFELs operated in the hard X-ray region, third-generation synchrotron radiation facilities, and EUVL performed in the soft X-ray region. Furthermore, aspherical mirrors are preferable to spherical mirrors for use as optical elements in imaging devices in artificial satellites because aspherical mirrors can improve the optical characteristics (such as brightness and resolution) of the resulting images and reduce the weight and size of the optical system. The lenses used for this purpose have asphericities of greater than 100 μm, so their shape errors should be 10 nm PV or less.

To realize the next-generation ultra-high-precision mirrors and lenses described above, significant progress in ultra-high-precision measurement and machining technology is essential. The measurement technique used during processing must have an accuracy of better than one order of magnitude compared to processing accuracy. To measure undulations and surface variations at spatial wavelengths of less than 1 mm, atomic force microscopy, scanning tunneling microscopy, and scanning white-light interference microscopy are presently capable of achieving the required accuracy. On the other hand, to measure shape variations at spatial wavelengths of more than 1 mm, phase-shift Fizeau interferometry, and coordinate measuring machines have been utilized. However, these techniques require using reference plane and linear motion for comparison and the necessary shape measurement accuracy of 1 nm PV is not achievable for aspheric surfaces [1].

In the researches of X-ray mirror [2–5], various approach of figure measurement is developed. X-ray mirror for example KB mirror have aspheric figure component in one-dimensional (1D) direction. 1D direction aspheric mirror that is fabricated in sub nanometer accuracy using elastic emission machining (EEM) [2] can be measured by stitching interferometer with an accuracy of single nanometer PV [3]. And, in 1D aspheric mirror, 1D profile can be measured by long traced profiler [4]. There are also cases where a two-dimensional (2D) profile is obtained by using Shack-Hartmann sensor [5]. However, it is difficult to measure elements having a small radius of curvature of 1 m or less by these methods. In fact, high precision optical elements having a smaller radius of curvature or 2D aspherical components are required in industry.

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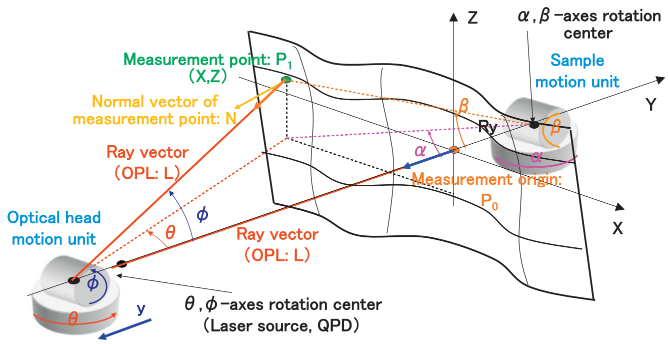

Fig. 1. Three-dimensional (2D profile) measurement system principle.

2D aspheric optical component that have small radius of curvature can be measured by interferometer using null lens or computer generated hologram (CGH). However, it is not easy to realize a highly accurate null lens or CGH. It is also necessary to prepare different null lenses for each measurement aspherical surface. Interferometer using null lens is highly cost. There is also commercially available stitching interferometer for aspheric objects. However, there is concern about stitching error. Thus, there is no method capable to measure 2D aspheric optical component with single nanometer accuracy.

To meet the above requirements, we developed a nanoprofiler in which the error is reduced because of the encoder calibration [6] and the optical system design [7], enabling high-precision measurements of spherical and plane surfaces [8,9]. We previously measured a radius of curvature 1000 mm concave mirror using the developed nanoprofiler and achieved sub-nanometer measurement repeatability. Furthermore, the difference between the measurements obtained by using the nanoprofiler and an interferometer was less than the systematic error [10]. However, the 1000 mm sample was spherical, as are the surfaces for which high-precision interferometer measurements are available, and measurements of shapes more complex than spherical surfaces were necessary to verify the free-form measurement accuracy of the proposed nanoprofiler. As such a complex-shaped sample, we employed an 2D aspheric mirror in this study. Both machining and measurement of aspheric shapes are difficult. Nevertheless, the nanoprofiler proved capable of performing measurements with sub-nanometer repeatability. Furthermore, the difference between the results obtained by using the nanoprofiler and an interferometer with a null lens was less than the systematic error. These results, which are presented herein, demonstrate that the nanoprofiler can accurately measure samples with many degrees of freedom that are difficult to measure by using interferometers.

2. Nanoprofiler

The principle of the fast nano-precision shape measurement method is shown in Fig. 1, in which the normal vector traces for the investigated aspheric surface are depicted. In this method, the laser beam and rotational motion, which is more accurate than translational motion, and the shape is determined based on the coordinates and the normal vector of each point on the mirror [10,11]. The four goniometers in this system are each adjusted so that the laser beam emitted from the light source is reflected by the mirror surface to the center of the quadrant photodiode detector (QPD), which is located at the optical equivalent of the light source, enabling the normal vector at the point at which the beam encounters the mirror surface to be obtained. The single-axis translation stage containing the two-axis goniometer, optical head with the light source, and QPD is referred to as the optical head motion unit. Similarly, the two-axis goniometer holding the sample is referred to as the sample motion unit. By changing the position of the goniometer in the sample motion unit along two axes, the coordinates of different points on the surface can be obtained. Simultaneously, the biaxial goniometer

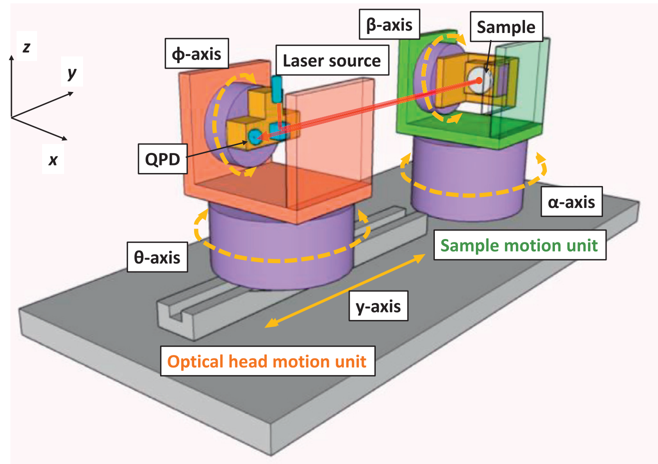

Fig. 2. Schematic of nanoprofiler.

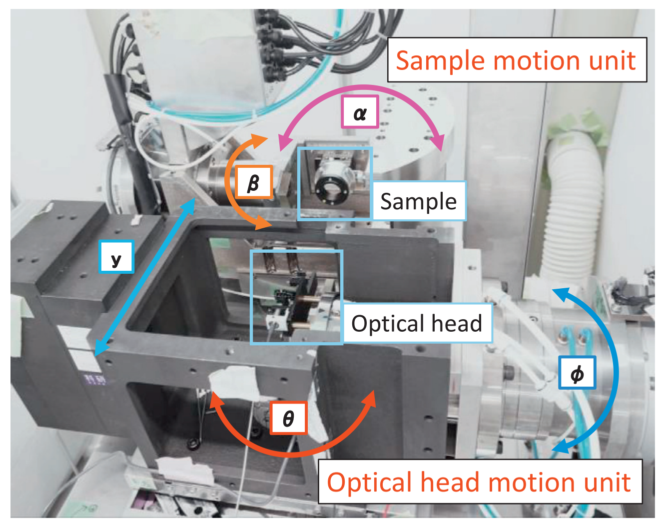

Fig. 3. Photograph of nanoprofiler.

in the optical head motion unit determines the normal vector at each point, and the translation stage moves along the y-axis to maintain a constant optical path length (OPL: L). Thus, motion occurs concurrently along five axes (θ, φ, α, β, y -axis), which are defined in Fig. 1. If the sample nominal figure specifications are known numerically, the stage position corresponding to each measurement point can be determined. Under the condition that the nominal shape information of the sample (position and normal vector) is known and the OPL is constant, it is possible to calculate the position of the 5 axis stage in the case where the laser is vertically incident on an arbitrary position of the sample. Using the derived stage positions, a numerical control program is created and is then used to scan the sample by adjusting all five axes simultaneously. The deviations of the sample shape from the nominal shape, i.e., the figure errors, are detected as deviations in the QPD. In this measurement method, there are no measurement geometry restrictions in principle, since no reference surface is required. Therefore, free-form surface shape measurements are possible [12].

A schematic of the nanoprofiler is presented in Fig. 2, and a photograph of the designed system is shown in Fig. 3. In the optical head motion unit, the goniometer can rotate independently along two axes (θ, φ-axis), and the translation stage moves along one axis (y-axis). The optical head mounted on the optical head motion unit and consisting of the laser light source and the QPD is placed at the rotation center of the two axes. The goniometer in the sample motion unit can also