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Estimation of systematic error of nanoprofiler using normal vector tracing method

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Abstract:
We have developed a nanoprofiler using the normal vector. The aim is to measure the free-form or aspherical high-precision. Since this method does not use a reference surface, it may be possible to measure the free form with high accuracy. Reproducibility of sub nm has been achieved so far. With the aim of the reduction and the evaluation of uncertainty, the estimation of the systematic error is attempted. We investigated the effect of systematic error has on the measurement result by computer simulation. Comparing the experimental results with the results, systematic errors are estimated.

Keywords: Nanoprofiler, Normal vector, Aspheric surface, High precision mirror

1. INTRODUCTION

With the development of facilities and devices using synchrotron radiation (SR), highly coherent X-ray light source (for instance, X-ray free-electron laser sources such as the SPring-8 Angstrom Compact Free-Electron) can be used nowadays. To develop practical application using such light source, high-accuracy aspheric mirrors which realize nanofocucing are demanded. In industry, high-accuracy aspheric mirrors are used in projection optical systems employed in demanding next-generation lithography applications using extreme ultraviolet or soft (13.5 nm wavelength) 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]. Such optical elements are needed to be fabricated and be measured precisely. Our purpose is developing measuring method which can be applied to next-generation high-accuracy aspheric or free-form optical elements. Currently most often measuring method is interferometers and coordinate measuring machines (CMMs). However, interferometers depend on the precision of an external optical reference, and CMMs are severely limited by the measurement angles that yield accurate results [3-4]. The novel methods such as a stitching interferometry [5] and a deflectometry [6] can measure aspheric or free-form surface but do not have enough accuracy. We developed a new type of nanoprofiler that traces 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 to the mirror surface, the normal vector of the each measured point of mirror is obtained. The optical motion system have two pairs of goniometers , on the other hand, the sample motion system have two pairs of goniometers and one linear stage. Using these five stages, the matching of incident and reflected light is realized. The normal vectors and their coordinates are acquired, and using these informations, the three-dimensional shape of mirror is calculated by a reconstruction algorithm. The profiler uses the straightness of laser light and not depends on reference surface accuracy. Free-form surfaces can be measured by proposed method. The profiler can measure the shape of the high-precision mirror reproducibility of sub-nanometer order. In order to enable an absolute surface figure measurement, it is necessary to know the uncertainty as well as the reproducibility of the surface figure measurement. And, uncertainty of measurement is dominated by systematic errors. Then, by numerical simulation of the error, it is investigated that the effect of systematic errors to give surface figure measurements. The assembly errors of 6 degrees of freedom (3-axis rotation and 3-axis translation) are given in the assembly of the stages sample, QPD, laser. Effects of each error which give the surface figure measurement is obtained. We tried to be reproduced the figure obtained from the experiments of the surface figure measurement by the combination of the figure due to the influence of the systematic error obtained by the simulation. Systematic error parameters in the condition that is reproduced surface figure, are close to the assumed systematic errors of fact. Thus, it is possible to calibrate the surface figure measuring approximately from systematic error which is given by simulation.

2. NANOPROFILER

Figure 1 illustrates the principle underlying the proposed profiler, which is based on the straightness of laser light and the high accuracy of rotational goniometers [7–8]. Our device for proposed measuring method is composed of the optical head motion unit and sample motion unit. The optical head motion unit consists of two goniometers (rotating around the θ- and φ-axes, respectively), one linear motion stage (moving along the y-axis), and a sample motion unit consisting of two goniometers (rotating around the α- and β- axes, respectively). Using this setup, the normal vectors and coordinates of measurement points on a sample can be determined. A laser light source and quadrant photodiode (QPD) detector are installed at optically equivalent positions. That position is at the rotation centers of the goniometers of the optical head motion unit. By so as to match the incident light and the reflected light, the objective coordinates and normal vectors at a measurement point can be obtained. To achieve this, the motions of the four goniometers are used to control the reflected light so that it continually returns to the center of the QPD. hile the measurement is being performed, the optical path length (L) is kept constant by controlling the linear motion stage. Using the coordinates of the goniometers and the linear stage, the coordinates of each normal vector can be determined. The information of the normal vectors and coordinates of measurement points used to reconstruct a surface shape through original algorithm. As described above, the profiler requires no reference mirrors. Therefore, the profiler can measure any shape (free-form) in principle [9].

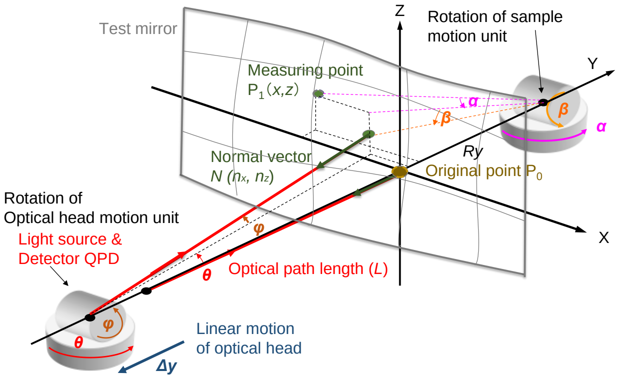


Fig. 1: Principle behind profile measurement system [10]

Figures 2 shows a schematic view of the nanoprofiler and figure 3 shows a photograph of the nanoprofiler. The machine operates on 6 motion axes, using one linear motion stage in the optical head motion unit (YF-axis), one linear motion stage of the adjustment in the sample motion unit (YW-axis, omitted in figure), two sets of twin goniometers in the optical head motion unit (CF-, AF-axes for *θ*-, *φ*-directions), and a sample motion unit (CW-, AW-axes for *α*, *β*-axes). The resolutions of the linear motion stage and the goniometers are 1 nm and 0.035 µrad, respectively. With the five axes controlled numerically, a laser beam scans the surface of the sample and the QPD detects the reflected laser point; the distance of this point from the center of the QPD has the information of the normal vectors. TThe length of the optical path between the QPD and the sample surface is constant in this paper, 400 mm.

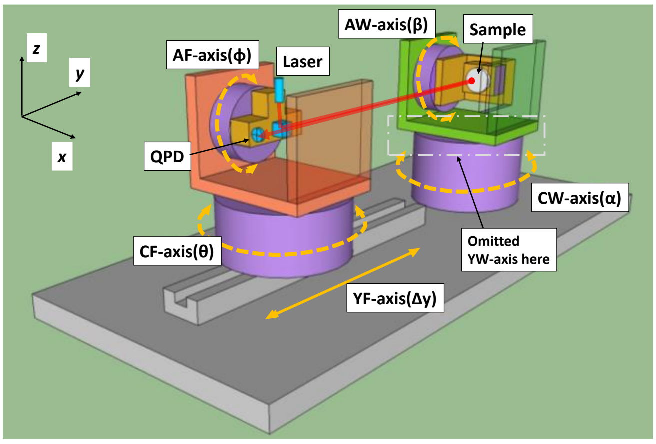


Fig. 2: Schematic view of nanoprofiler

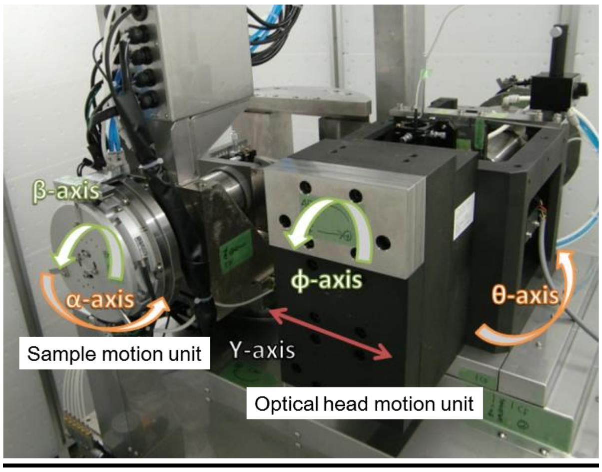


Fig. 3: Photograph of nanoprofiler [10]

3. SYSTEMATIC ERROR ANALYSIS BASED ON SIMULATION

We carried out the analysis of systematic errors. Giving a systematic error of 6 degrees of freedom to the stage assembly of six of the device and to the sample, QPD, laser assembly. As shown in figure 4, YF is a translation stage in the y-axis direction is placed in the optical head motion system, c-axis rotary stage CF is placed on the YF, a -axis rotary stage AF is placed on the CF. On the other hand, sample motion system is assembled in the order c-axis rotation stage CW, Y-axis translation stage YW, in the a-axis rotation stage AW from the bottom. YW is adjustable stage, are not used for actual measurements. Measurements were performed simulation of concave spherical surface of R = 400 mm, respectively YF-on-G, CF-on-YF, AF-on-CF, CW-on-G, YW-on-CW, the AW-on-YW assembly error of 6 degrees of freedom is given to.

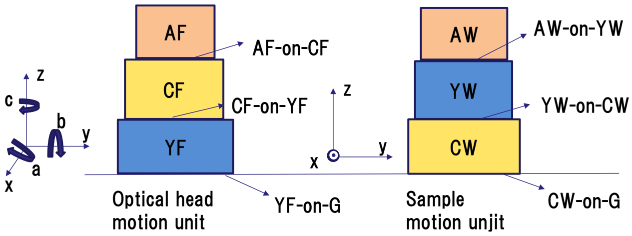


Fig. 4: Schematic view of the stage assembly order of nanoprofiler

Impact on the measurement results due to the influence of the systematic error is shown in figure 5-8. Distribution of four appears typically. Tilt component in the x-direction as shown in Figure 5 appears as the influence of systematic errors c-axis, the x-axis. Along with the change in the size of the systematic error, figure error that appears to change linearly. The linear changes are confirmed in all cases. Parabolic distribution to appear in the y direction as shown in Figure 6, it is the effect of systematic errors in the y-axis in AF-on-CF. This distribution is a singular distribution appearing only the AF-on-CF, y-axis. Shown in Figure 7, it is the distribution of the impact of a systematic error-axis, the x-axis. It has a tilt component in the y-direction. Distribution of the paraboloid of Figure 8 is the effect of systematic errors in the y-axis direction excluding AF-on-CF. Using the distribution of these changes linearly with changes in systematic errors, systematic errors of the apparatus is estimated from experimental data. Sensitivity of the effect of systematic errors are shown in Table 1. Sensitivity is that of the change in the PV value due to changes in the systematic error. Since the optical path length is 400mm, the measurement object is a condition of R = 400mm, change a, b, and c-axis has little effect on the measurement results only errors in the sample motion stage system are affected. Using the data of Figure 5-8, he systematic error is estimated by applying the least square method to the experimental data. Since, as shown in Table 1, there is a portion where there is a difference in sensitivity estimation is not a complete, but is estimated based on the typical values.

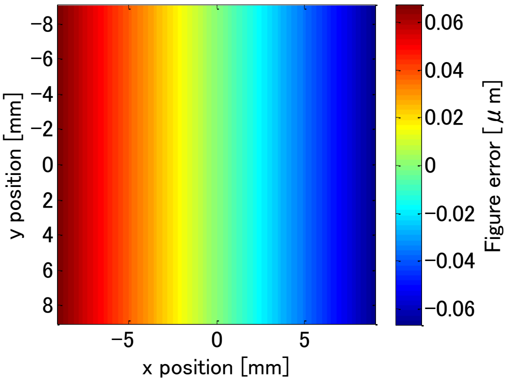


Fig. 5: Figure error by the influence of systematic errors c, x-axis (AF-on-CF, x-axis)

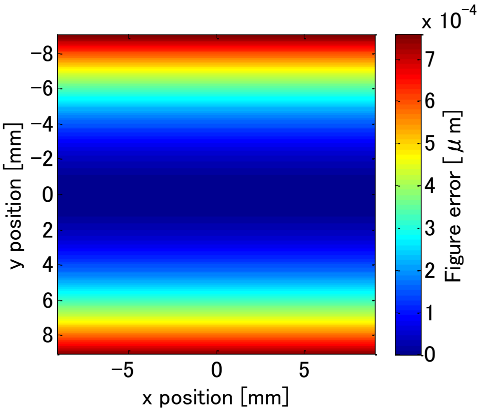


Fig. 6: Figure error by the influence of systematic error AF-on-CF, y-axis

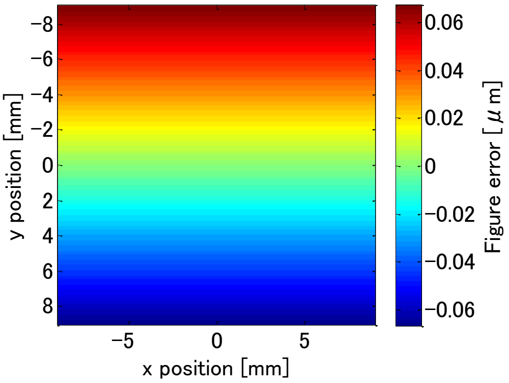


Fig. 7: Figure error by the influence of systematic errors a, z-axis (AF-on-CF, z-axis)

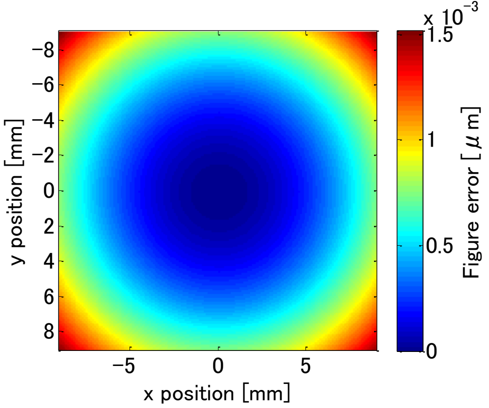


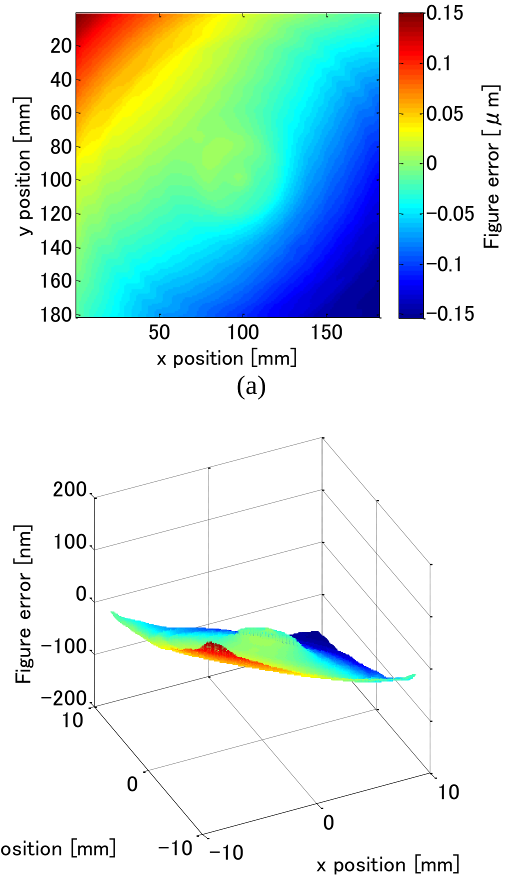
Fig. 8: Figure error by the influence of systematic errors y-axis except AF-on-CF (CF-on-YF, y-axis)

Table 1: Sensitivity of the effect of systematic errors

	a[nm/µrad]	b[nm/µrad]	c[nm/µrad]	x[nm/µm]	y[nm/µm]	z[nm/µm]
AF-on-CF	NA	NA	NA	4.50E+01	2.53E-01	4.50E+01
CF-on-YF	NA	NA	NA	4.50E+01	5.07E-01	4.50E+01
YF-on-G	NA	NA	NA	4.50E+01	5.07E-01	4.50E+01
AW-on-YW	1.80E+01	NA	1.80E+01	4.50E+01	5.07E-01	4.50E+01
YW-on-CW	1.80E+01	NA	1.80E+01	4.50E+01	5.07E-01	4.50E+01
CW-on-G	1.80E+01	NA	1.80E+01	4.50E+01	5.07E-01	4.50E+01
Sample	1.80E+01	NA	1.80E+01	4.50E+01	5.07E-01	4.50E+01
QPD	NA	NA	NA	2.25E+01	NA	2.25E+01
Laser	NA	NA	NA	2.25E+01	4.38E-08	2.25E+01

4. SYSTEMATIC ERROR ESTIMATION OF NANOPROFILER

Measurement of R=400 mm concave spherical have been performed 15 times. An example of the measurement results are shown in figure 9. As shown, the effect of the slope of the linear is out greatly. PV value is 361 nm. Using the distribution of Figures 5-8, the fitting is performed to the experimental data of 15 times. Parameters obtained by fitting are shown in Table 2. It is possible to estimate the amount of systematic error present in the entire apparatus from the average value of the parameter. These values are close to the assumed valued occurred in the device during assembly. Effect of the inclination of the primary was estimated that systematic errors of 3µm was affected approximately in terms of z-axis displacement of AF-on-CF and x-axis displacement of AF-on-CF. Since the standard deviation is also sufficiently small value, it is a reasonable estimation. It was estimated in the same way for displacement of y-axis AF-on-CF, and y-axis of CF-on-YF but the standard deviation is large. This is because both the figure 6 and figure 8 have a component of the parabolic similarly, they are not linearly independent. Estimate of the systematic errors of the y-axis is ambiguous, but that the effect of errors in the y-axis is large relative error of x, z-axis was confirmed. This is due to the configuration of the device, adjustment of the y-axis is the most difficult. The error of y-axis will be calculated separately by using a self-calibration method etc., and then perform the comparison with the present technique. Mean values estimated in table 2 is considered to be a systematic error, it was fitted to the experimental data. The average data of 15 is shown in figure 10. PV value is 107 nm. Effect of the inclination of the primary is not present. The end of the measurement region, the influence of the paraboloid of the secondary may have been confirmed. However, it has become a flat enough distribution in the measurement area near the center. It is estimated distribution of the end of the measurement area of figure 10 is to be derived from components other than parabolic. Whether this distribution is caused by the sample shape or the impact of the error is not considered will be verified.



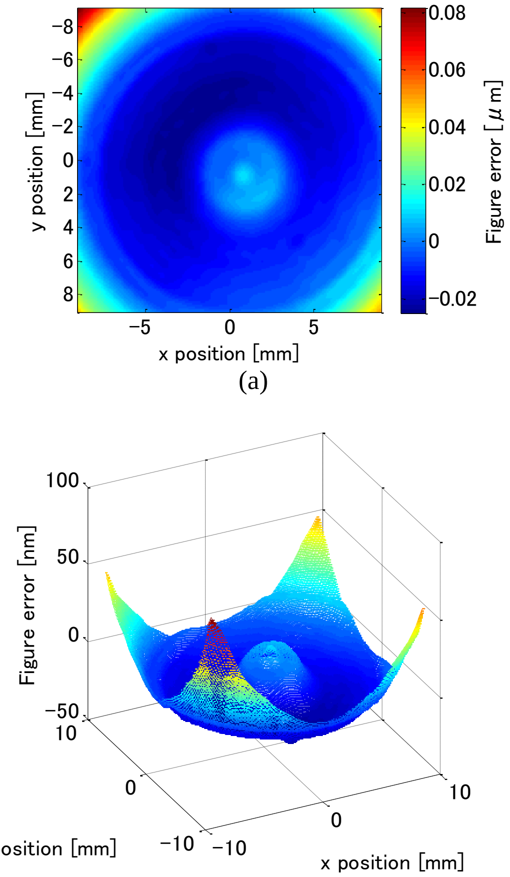
(a)

(b)

Fig. 9: Experimental data measuring R=400 mm concave mirror (a) 2-D, (b) 3-D display

Table 2: Experimental results for lens effect of the trapped microsphere.

	Average of systematic error parameter (μm)	Standard deviation (σ)
AF-on-CF, x-axis	-2.9049	0.0494
AF-on-CF, y-axis	35.9916	3.8918
CF-on-YF, y-axis	110.606	4.6595
AF-on-CF, z-axis	-3.167	0.0397



(a)

(b)

Fig. 10: Average data of experimental data after systematic error correction (a) 2-D, (b) 3-D display

5. CONCLUSION

With the aim of reducing the uncertainty in nanoprofiler that we are developing, systematic error estimation is carried out. The systematic errors here, are errors of 6 degrees of freedom of the assembly sample, QPD, laser also errors in 6 degrees of freedom of the assembly portion of the stages. Concave spherical measurement of R=400 mm has been assumed. Influence of the systematic errors are calculated by simulation. The results are as follows:

・It was confirmed that the figure error s of slope of the linear, parabolic quadratic and the paraboloid appears.

・That according to the increase or decrease of the systematic error, shape error varies linearly has been confirmed.

By using these properties, and fitting the experimental data, systematic errors with the device was estimated. Measurements of 15 times were used. The value of systematic error has been translated at the typical values. The results are as follows:

・Components that affect the slope error of the first order, was about 3μm both the x, z-axis in the entire device. Standard deviation is small, the accuracy of the estimate is high.

・Error in the y-axis direction that affect parabola of the secondary, the error of the paraboloid, was 36μm, and 110μm respectively, in the entire device. Standard deviation is large in this result, accuracy is not high. But it was confirmed to be a large value as compared x, and z-axis component. This is a predictable results from device configuration. For the deviation of the y-axis, the validity is verified in comparison with other methods, such as self-calibration.

・As a result of correcting the experimental data using a systematic error that is estimated, tilt component can not be confirmed. However a large component of the curvature was observed in the measurement region outside. Whether this component is from sample form or from error will be verified in the future.

As verification of the method, measuring the assembly error of the apparatus, and comparing the results will be carried out.

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