XXI IMEKO World Congress "Measurement in Research and Industry"
August 30 – September 4, 2015, Prague, Czech Republic

SELF-CALIBRATION FOR OPTICAL PATH LENGTH OF 3D NANOPROFILER CONSIDERING RANDOM ERROR

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Abstract – In 3D nanoprofiler we develop, the optical path length is the largest uncertainty factor. As a method for self-calibration of the optical path length, we propose a method of utilizing a known optical path length shift. Results of simulation considering the random error, the accuracy was found to be dependent on 3 parameters. Similar characteristics is confirmed by experiment. Optical path length has been determined by the order of under four digits.

Keywords: nanoprofiler, self-calibration, optical path length, direct measurement, free-form

1. INTRODUCTION

High-accuracy aspheric or free-form optical elements are demanded nowadays. To develop practical application using X-ray light source (for instance, X-ray free-electron laser sources such as the SPring-8 Angstrom Compact Free-Electron, extreme ultraviolet used for lithography), high-accuracy aspheric mirrors are needed. Free-form optical elements with radius of curvature of less than 10 mm are now employed for consumer products represented by digital cameras [1]. For the processing of high accuracy, accurate measurement method is essential. The measuring methods such as interferometers and coordinate measuring machines (CMMs) are used for that matter, but that accuracy are not enough for these demands [2–3]. The novel methods which aim to measure aspheric or free-form surface such as a stitching interferometry [4] and a deflectometry [5] also do not have enough accuracy.

To meet the demands, we developed novel 3D nanoprofiler that traces the normal vector of a mirror's surface. The normal vector is measured using the straightness of laser light. The optical motion system which determine the direction of laser propagation, have two pairs of goniometers. And the sample motion system has two pairs of goniometers and one linear stage. By synchronous drive of the stages, the incident light and reflected light to the mirror surface is made to be coincident, and then normal vector is obtained. Our measuring method uses the information of the normal vector and coordinates of each measuring point. This information is post-processed by a reconstructed algorithm, and the 3D surface figure is obtained. The profiler does not depend on reference surface accuracy, and free-form surfaces can be measured by proposed method. Proposed method using nanoprofiler have possibility to realize the absolute surface figure measurement of next-generation high-accuracy mirror. It is confirmed that developed nanoprofiler have the repeatability of sub-nanometer scale by experimental evaluation [6]. By calibrating the systematic errors present in the nanoprofiler, a challenge is to perform the reduction of uncertainty.

As a first step, we propose a method of calibrating an optical path length between the optical system and the sample system is the most uncertain in the assembly error of the nanoprofiler. This approach uses the additional information due to the shifting the optical path length in the known length. In this paper, the characteristics of the proposed self-calibration method with random error is verified by computer simulation and experiment As a result, it was confirmed that the accuracy of self-calibration is increased under the following conditions.

- Many steps of the optical path length shift.
- Large shift amount of optical path length.
- Small radius of curvature of the sample shape.

Optical path length has been determined by the order of under four digits by experiment. In this paper, the best estimate is 398.750 mm, accuracy is 70.9 μm.

2. METHOD OF 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 measurement method involves two components: an optical head and a 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 and, through the application of an original algorithm, used to reconstruct a surface shape. A laser light source and quadrant photodiode (QPD) detector are installed at optically equivalent positions at the rotation centers of the goniometers of the optical head motion unit; by causing the optical paths of incident and reflected light to coincide, 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. During the measurement process, the optical path length (L) is kept constant by applying a numerically controlled shift to the position of the translational motion stage. Based on the coordinates of the goniometers and the linear stage, the coordinates of each normal vector can be determined. The profiler then calculates surface shapes from the normal vectors and coordinates determined by the algorithm by measuring the rotary motion of the goniometers, which is more accurate than measuring linear motion and requires no reference mirrors. Therefore, there are no limitations on which shapes can be measured and free forms can be directly mapped [9].

Figure 2 show a photograph of the nanoprofiler. The machine operates on five motion axes, using one linear motion stage in the optical head motion unit, two sets of twin goniometers in the optical head motion unit (*θ*-, *φ*- axes), and a sample motion unit (*α, β*-axes).

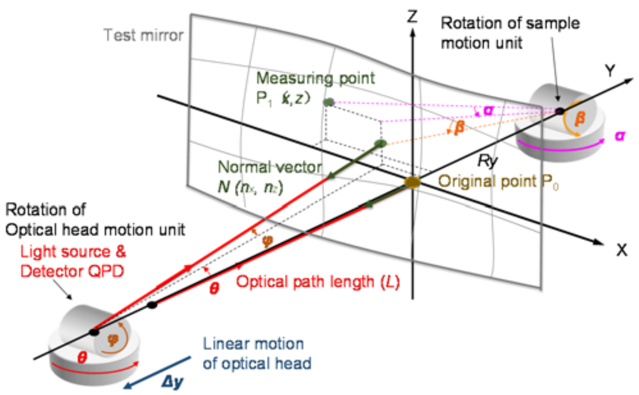

Fig. 1. Principle behind our system for profile measurement in two dimensions.[6]

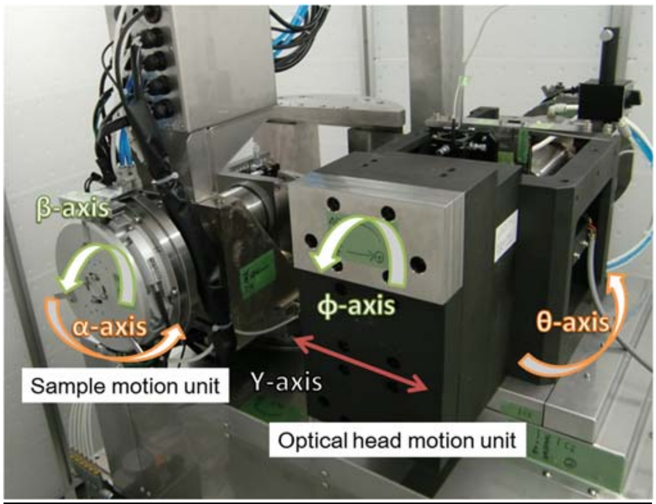

Fig. 2. Photograph of nanoprofiler.[6]

3. PRINCIPLE OF SELF-CALIBRATION FOR OPTICAL LENGTH

3.1. Principle of basic 2 step self-calibration

The principle of self-calibration method of the optical path length is described below. Initial optical path length L is set to about 400mm, but the error of about several hundred micrometers may occur in the setting of the current state of the device. The optical path length L is unknown. On the other hand, with respect to ⊿L a deviation from the initial path length, it can be determined in nm resolution accuracy of the translational axis. ⊿L is known. And adding information known ⊿L, proposed self-calibration method determine the optical path length L by using adding known information of ⊿L and an iterative numerical calculation. The schematic diagram of ⊿L shift is shown in Figure 3. After the measurement of a sample that is set in the initial optical path length L, the optical path length is shifted by ⊿L. Sample is measured again after the shift. Sample shape is derived by using measured data before and after shift, and further using any optical path length La. Difference occurs between both the results. This difference is derived from the error between the true optical path length L and the set optical path length La. If L and La match, shape derivation results match. While changing the set optical path length La, and searches the La like shape derivation results match. The evaluation value is used the average of the sum of squares between each measurement. The above is an example of a single optical path length shift, referred to as 2-step self-calibration. Because it contains random errors in the actual experiment, it is necessary to consider the effect. In this paper, we investigate the effect.

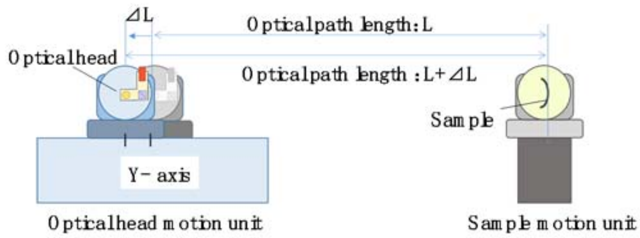

Fig. 3. Schematic diagram of ⊿L shift

3.2. Principle of multi-step self-calibration

Actually, the calculation of the optical path length L by the effect of random errors result does not converge uniquely. Therefore, because of the influence reduction of random error, multi-step self-calibration is introduced. The shift of the known ⊿L is performed several times, the measurement is performed. Evaluation value is the average value of the standard deviation at each measurement point coordinates between the measurement results. The following (1), (2) are used. Equation (1) represents the average value of the shape derivation result of each coordinates in each step. The formula y (x, L) represents, the shape derivation result in the coordinates x and trial optical path length L.N is the number of steps. a, b show the measuring range .In (2) , using (1) , calculates the standard deviation , and using that value as an evaluation value. By performing the iterative calculation, and calculates the La approximating the true. With this technique, the dispersion of the convergence value is expected to be reduced. By consideration by pre additional systematic error analysis performed, the error in the optical path length by suppressing the μm order, it has been shown to be achievable shape uncertainty 1 nm PV optical path length factors [10]. In this paper, we consider the conditions to achieve a dispersion in the convergent value of μm order.

$$m = \frac{\sum_{n=0}^{N-1} y(x, L+n\Delta L)}{N} \quad (1)$$

$$T(L) = \sqrt{\frac{\frac{\int_a^b \sum_{n=0}^{N-1} |y(x, L+n\Delta L) - m|^2 \, dx}{N}}{(b-a)}} \quad (2)$$

4. SIMULATION ANALYSIS CONSIDERING RANDOM ERROR

In the proposed self-calibration method , in consideration of the random error, the condition for achieving the dispersion in optical path length convergence value of μm order is searched The effect of step number, ⊿L, and sample radius of curvature (R) is investigated. It is a qualitative analysis of the characteristics of the self-calibration. The simulation conditions are shown in table1.

4.1. Influence of step number

The effect of the number of steps is examined . The optical path length is set to the target setting value 400 mm of the actual apparatus . This is a measurement simulation of concave spherical mirror of radius of curvature (R) 400 mm. Since the least movement of the stage in relation to the optical path length , R = 400mm is employed as a standard sample. To reading error of the encoder for each axis as a random error. The influence of air fluctuations and heat are ignored. Because quantitative estimate of their effect is difficult in current situation Thus random error of the simulation of this paper is estimated smaller than the actual condition . ⊿L is set to 50μm. The number of steps is set to 2, 3, 4, 5, 7, 10. To investigate the effect of random errors, 10 trials are performed in each condition. Search resolution of the optical path length in the vicinity of the convergence value is 100 nm. In Figure 4, the behavior of the evaluation value with respect to the optical path length estimate value La in self-calibration method is shown. Figure 4 (a) is an example that has not been introduced random error. It can be confirmed that it converges to the set optical path length 400 mm at any number of steps. Figure 4 (b) is an example of the introduction of random error. It is confirmed that there is a dispersion in the convergence value by the number of steps. Depending on the number of steps there is a difference in the slope of the evaluation value. The more the number of steps is large , the inclination is increased. The more the inclination is large, it is expected that the effect of random errors is reduced. It should be noted that since the evaluation value calculation method in 2-step self-calibration is different from others, it is displayed as a reference value.

Dispersion in the convergence value at each step number is evaluated. In figure 5, the dispersion in the degree of convergence value at the time of the 2-step self-calibration is shown. In figure 6, the case of 10-step self-calibration is shown. In figure 5, dispersion of about 10μm is observed . On the other hand in figure 6, dispersion of about 1μm can be observed. Changes in the average value of the convergence value is shown in figure 7 (a). The average value of the convergence value has remained in the vicinity of about 400 mm. Tendency to approach the true value as the number of steps increases is confirmed. Standard deviation of the convergence value is displayed as an error bar . Figure6 (b) shows the transition of the standard deviation of the convergence value. The more the number of steps increases, it is confirmed that the standard deviation is small. From the above results, it is confirmed that the larger the number of steps, the dispersion of the convergence value expected to decrease, and also accuracy of the convergence value expected to increase.

Table 1 Simulation setup

Optical path length	400 mm
Sample shape in 4.1. , 4.2.	R = 400 mm concave
Sample shape in 4.3.	R = 100 mm, 400 mm, 1000 mm concave
Rotational reading error	0.1 nrad (σ)
Translational reading error	1 nm (σ)
QPD reading error	1 nm (σ)
Shift amount of optical path length (⊿L) in 4.1.	50 μm
Shift amount of optical path length (⊿L) in 4.2.	50 μm, 100 μm, 200 μm
Shift amount of optical path length (⊿L) in 4.3.	200 μm
Step number	2, 3, 4, 5, 7, 10
Trial times	10

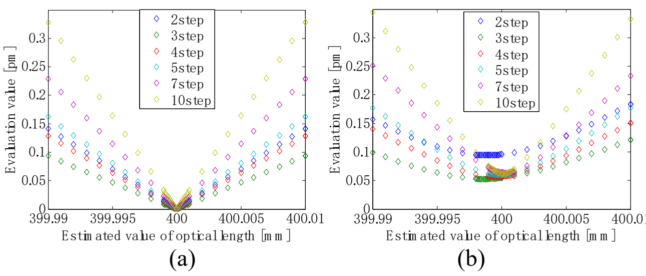

Fig. 4. Evaluation value of self-calibration (a) without random error, (b)with random error

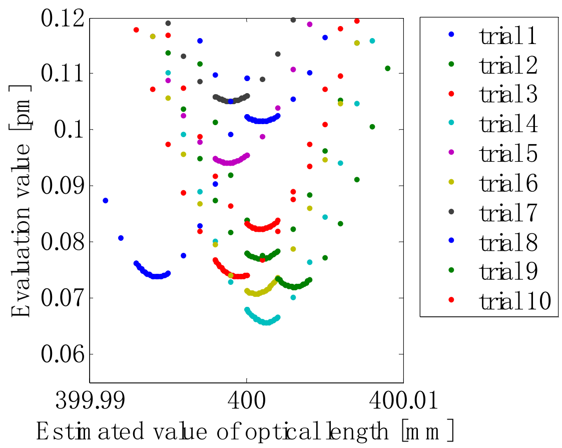

Fig. 5. Dispersion of the convergence value (2 step self-calibration)

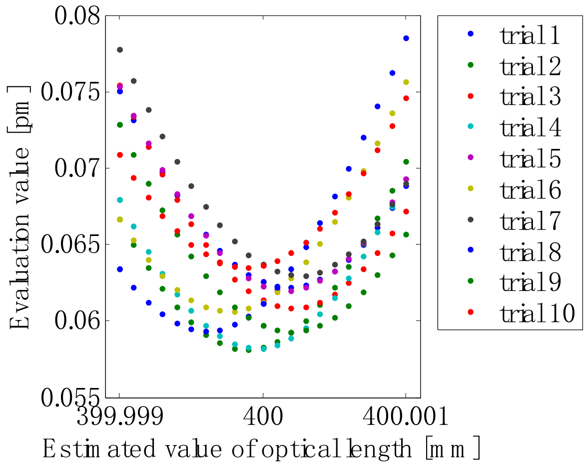

Fig. 6. Dispersion of the convergence value (10 step self-calibration)

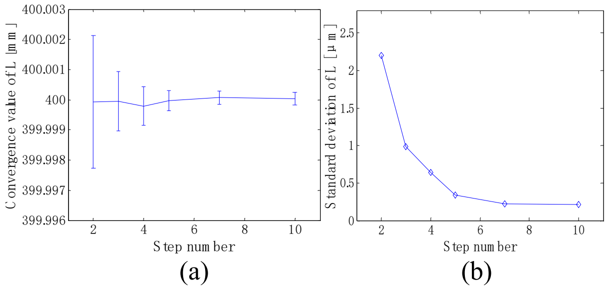

Fig. 7. Evaluation of self-calibration (a)Average of convergence value, (b)Standard deviation of convergence value

4.2. Influence of shift amount of optical path length

The effect of shift ⊿L has on the convergence result is considered. ⊿L was set to 50, 100, 200μm. Shift amount upper limit is a 200μm. When performing the self-calibration 10step at 200μm, the total shift amount is 1.8 mm. Due to the limitations of an actual device, the shift amount of 1.8 mm is close to the realistic limit amount. Shift amount upper limit is determined by this limitation. The behavior of the evaluation value in 10-step self-calibration is shown in Figure 8 (a). The larger the ⊿L, the slope increases. The slope is large, i.e. the change in evaluation value is large means that the influence of chance is included in the measurement error becomes smaller .The greater ⊿L, dispersion in the convergence value is it is presumed small. In Figure 8 (b), the behavior of the standard deviation of the convergence value due to the change in the step number and ⊿L is shown. The greater ⊿L, it was confirmed that the dispersion is suppressed.

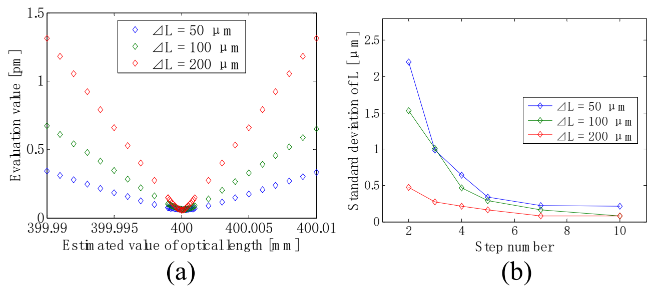

Fig. 8. Self-calibration simulation varing shift amount of optical length (⊿L) (a)Evaluation value of self-calibration, (b)Standard deviation of convergence value

4.3. Influence of sample radius

The effect of curvature of the sample gives the convergence result is considered. Curvature radius R is set to 100, 400, 1000mm. ⊿L is set to 200μm. In Figure 9 (a), the behavior of the evaluation value in the 10-step self-calibration is shown. As R decreases, the slope increases . As R becomes smaller, it is presumed dispersion in the convergence value becomes small. In Figure 9 (b), due to changes in the step number and the radius of curvature, the behavior of the standard deviation of the convergence value is shown. The more the radius of curvature is small, it was confirmed that the dispersion is suppressed.

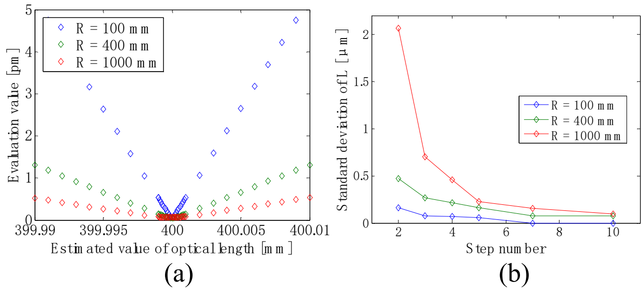

Fig. 9. Self-calibration simulation varing radius of curvature of the sample (R) (a)Evaluation value of self-calibration, (b)Standard deviation of convergence value

5. EXPERIMENTAL VERIFICATION

Characteristics obtained by the simulation is verified experimentally.The effect of step number, ⊿L, and sample radius of curvature (R) is investigated. Then, the optical path length determination is attempted in the best conditions in the simulation. The experimental conditions are shown in table2.

Table 2 Experimental setup

Optical path length	About 400 mm
Sample shape in 5.1.	R = 100 mm, 400 mm concave
Sample shape in 5.2.	R = 100 mm concave
Shift amount of optical path length (⊿L) in 5.1.	200 μm
Shift amount of optical path length (⊿L) in 5.2.	50 μm, 100 μm, 200 μm
Step number	3,6,10
Trial times	20

5.1. Influence of sample radius

The effect of curvature of the sample is investigated experimentally.Samples employed are R = 100 mm and 400 mm concave mirror. ⊿L is set as 200 μm, and step numbers are 3, 6, 10. The resuls is evaluated in Figure 10. Figure 10 shows the behavior of the standard deviation of the convergence value. As the radius of curvature is small, as well as simulation, it is confirmed that the dispersion of the convergence value is small. Also, the more the number of steps, the dispersion of the convergence value is small. However, standard deviations are 3, 4 -digit large compared to the simulation. It has been shown that a large effect of random errors than conditions given in the simulation in the actual measurement environment. Also, it is assumed that pitch yaw of the translation stage, the shape errors of the samples are affected.

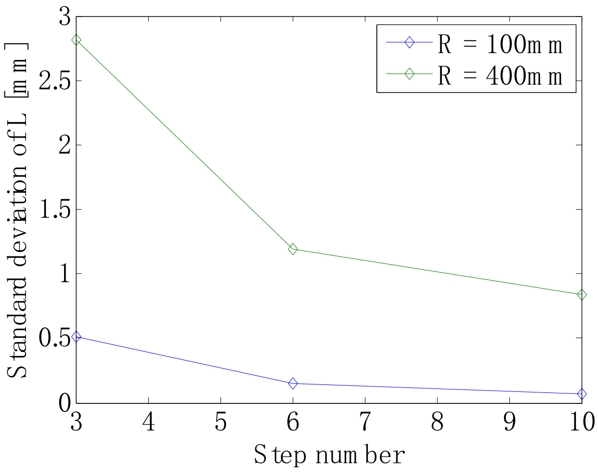

Fig. 10. Dependency on the curvature radius of the standard deviation of the convergence value

5.2. Influence of shift amount of optical path length

The effect of shift ⊿L is investigated experimentally. Sample employed is R = 100 mm concave mirror. ⊿L is set as 50 μm, 100 μm, 200 μm, and step numbers are 3, 6, 10. The results are evaluated in Figure 11 and 12. It shows the changes in the average value of the convergence value in Figure 11. The larger ⊿L, the average value of the convergence value it can be confirmed to be stable.Figure 12 shows the behavior of the standard deviation of the convergence value. As well as simulation, as ⊿L is large, dispersion of convergence value is small. Compared to the simulation, it can also be confirmed that the digits of the dispersion of the convergence value is large.The result in the best conditions inthis paper is shown. The conditions are step number 10 , R = 100 mm, ⊿L = 200 μm. Convergence value average is 398.750 mm. Since the convergence value average is close enough to 400 mm of the system design values, it is considered to be a reasonable value. Also the standard deviation of the convergence value is 70.9 μm. It does not reach the goal of μm order. In the future work, taking advantage of the knowledge obtained in this paper, the accuracy is pursued experimentally.

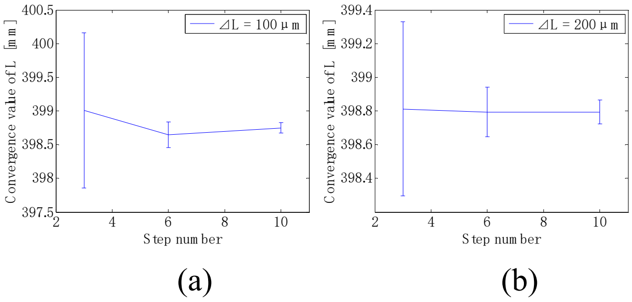

Fig. 11. Average of convergence value (a)⊿L = 100 μm, (b)⊿L = 200 μm

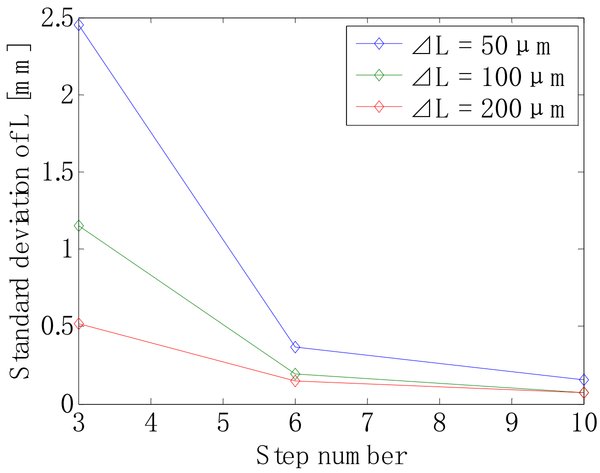

Fig. 12. Dependency on ⊿L of the standard deviation of the convergence value

6. CONCLUSIONS

In nanoprofiler we have developed , the error in the optical path length is the most uncertain . As a method for estimating the optical path length in the error of sub-μm, we have proposed a self-calibration method . It is a technique that utilizes information of known amount shifting of the optical path length. By simulation that takes into account the random error, the following findings were obtained .

・ The more the number of steps is large, the average value of the convergence value approaches the true value.

・ The more the number of steps is large, the dispersion of the convergence value can be suppressed. As compared to the 2-step, 10-step self-calibration is one order of magnitude smaller dispersion.

・ The more the optical path length shift amount is large, the dispersion of the convergence value can be suppressed. If ⊿L is 200μm, when compared to 50μm, about 4 times the dispersion is small.

・ The more the radius of curvature of the sample is small, the dispersion of the convergence value can be suppressed. Between the curvature radius and the dispersion of the convergence value, there is some degree of proportionality.

・ In the condition of 10-step self-calibration, ⊿L = 200μm and R = 100mm, it was confirmed that the dispersion of the convergence value can be suppressed to less than search resolution 100nm.

It was found that accurate optical path length estimation can be realized by the number of steps increase, ⊿L increase, and R of sample decrease. However, in the actual measurement environment, there are larger random errors than the random error that is set in this paper.

By actual measurement experiment, we examined the characteristics obtained in the simulation. Qualitative characteristics were matched by simulation and experiments. However, the dispersion of the convergence value that is confirmed 3, 4 magnitude larger compared with the simulation. As this reason it considered the following.

・ Random error parameters that are given in the simulation is small.

・ Pitch and yaw of the translation stage is affecting.

・ Figure error with the sample is affected.

In the future work, by performing the optimization of the experimental conditions, we will pursue the optical path length estimation accuracy. In addition, it is investigated the effect of systematic errors give self-calibration method.

ACKNOWLEDGM. 73ENTS

This work was carried out at the Ultra Clean Facility, Osaka University. This work was supported by Grants-in-Aid for Scientific Research (no.22226005) from the Ministry of Education, Culture, Sports, Science and Technology.

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