NANOMETER PROFILE MEASUREMENT OF LARGE ASPHERIC OPTICAL SURFACE WITH IMPROVED DEFLECTOMETRY METHOD
- Principle Introduction and Experimental Verification -

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Abstract: Deflectometry methods are widely used for flatness measurement of optical surfaces with sub-nanometre uncertainty. In the other hand, the limitation of measuring range of the autocollimator makes it unavailable for surfaces with large angle change. In this paper, a new method is proposed to enlarge the measuring range of the autocollimator so that surfaces with large slope change are measurable. The data processing methods are introduced and experimental setup is built. A concave mirror with large slope change is measured to verify the basic principle of proposed method. The experiment result proved that the measuring range of deflectometry method is enlarged with proposed method. The repeated experiments result shows that the repeatability of the measured profile is less than 15 nanometers.

Keywords: aspheric surface, profile measurement, deflectometry, measuring range enlargement

1. INTRODUCTION

Large aspheric optical surface with high accuracy are widely used in huge telescopes and large synchrotron radiation facilities. The size of the large surfaces is from hundreds of millimetres to several meters and the profile accuracy of them is usually hundreds of nanometers. For that reason, the profile measurement of these surfaces is required with uncertainty of tens of nanometers.

As shown in Fig. 1, for near flat surfaces and spherical surfaces, interferometric methods are the most popular measurement methods for their high accuracy and high efficiency. With null methods, computer generated hologram (CGH) and high accuracy stitching, slightly aspheric optical surfaces are also measurable with interferometric methods [1][2][3]. However, interferometric methods still face problem with high accuracy measurement of aspheric surfaces with large departure from perfect sphere. In the other hand, deflectometry methods are proposed for near flat surfaces measurement. The uncertainty for large near flats measurement is sub-nanometer [4]. However, because of the limitation of measuring range of the angle sensor, deflectometry methods are not available for profile measurement of surfaces with large slope change.

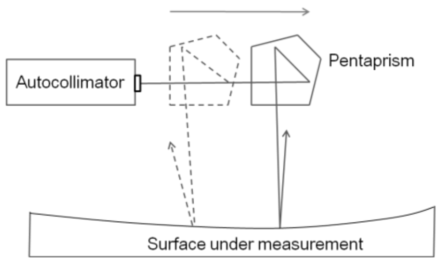

Fig. 1 Principle of scanning deflectometry method

In this paper, I have proposed a method for the enlargement of autocollimator using rotation stage. As a result, large aspheric optical surfaces with large slope change are measurable with our proposed methods. To improve the accuracy of our proposed method, a compensation method is proposed to eliminate the effect of pitch angle error of linear stage. And rotation accuracy effect of the rotation stage is also considered and a high accuracy detection method is proposed. Finally, an experimental setup is built based on proposed method and the measurement repeatability of the measurement facility is investigated [5].

2. PRINCIPLE

The traditional deflectometry method is not available for measurement of surfaces with large slope change. The main reason is the high accuracy autocollimator does not have large enough measuring range. And to solve this problem, in my proposed method a rotation stage is used to enlarge the measuring range of autocollimator [6].

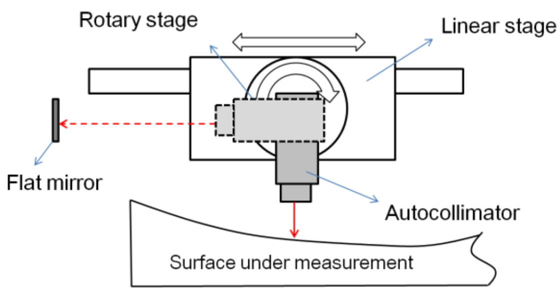

Fig. 2 Measurement of pitch error of linear stage before surface measurement

As shown in Fig. 2, a rotation stage is fixed between the linear stage and autocollimator. By translation of the linear stage, different part of the surface is able to be measured. When measuring surface with large slope, the rotary stage is used to help enlarging the measuring range. When the detected angle from autocollimator is going to exceed the measuring range of the autocollimator, the rotary stage turns a certain angle. As a result, the detected angle returns into the measuring range. Then the linear translation goes on to scan the whole surface.

Because the pitch error of the linear stage affects the angle measurement the measurement result very much, in our proposed method, we measured the pitch error of linear stage before using it and make compensation to the measurement result with the pitch angle data. As shown in Fig. 2, to measure the pitch angle of the linear stage, the autocollimator is rotated to the position parallel to the scanning direction of linear stage. A flat mirror is fixed on the table that vertical to the scanning direction. The autocollimator measures the angle change as the linear stage scans. The pitch error of the linear stage is then measured.

Since the positioning accuracy of the rotation stage affect the angle measurement result very much, the rotated angle of it should be detected with high accuracy with the same scale of the autocollimator. Since rotation stages with required accuracy are usually with extremely high price and also difficult to calibrate, in this paper a calculation method with high accuracy is proposed to detect the rotated angle of rotation stage.

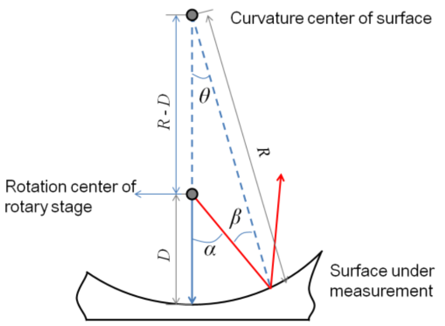

Fig. 3 The relationship between rotated angle α and autocollimator detected angle β

Fig. 3 shows the relation between autocollimator detected angle change β and rotated angle α. R is the curvature radius of the surface in the rotated part. Because α and θ are supposed to be an angle on the order of several hundreds of micro-radians, we can assume the circle arc length $R\theta$ is the same as the circle arc length $D\alpha$. As a result, the relationship between α and β is deduced as Eq. 1.

$$\alpha = \frac{R}{R-D}\beta \tag{1}$$

Since the distance change on the surface by the rotation is only several micrometer, the curvature radius R on the rotation part is considered the same with that before the rotation. And the curvature radius before the rotation is calculated from the least squire line of angle data detected by autocollimator. The distance D between rotation centre and sample is measured before the scanning.

3. DATA PROCESSING

To get the profile data of surfaces under measurement, there are mainly two data processing steps: angle connection and numerical integration.

Because of the rotation of the autocollimator, the detected angle data is interrupted. At the same time, the measured position on the sample surface also changes by S as shown in Fig. 4.

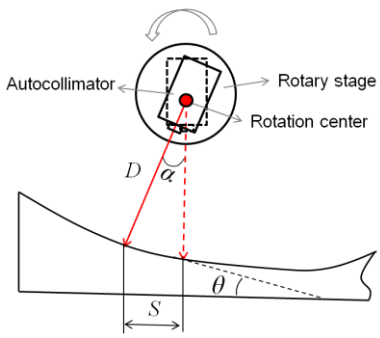

Fig. 4 Measuring place change by the rotation of rotation mirror

The connected angle data A_i of the surface is calculated using the raw angle data a_i detected by autocollimator and the rotation angle α_j of rotation stage as Eq. 2.

$$A_i = \sum a_i + \sum \alpha_j \tag{2}$$

In the equation, i is correspond to the number of raw angle data a_i, and j is the rotated times of rotation stage. The raw angle data a_i is with pitch angle compensation.

The connected angle data A_i does not only corresponds to the scanning distance of linear stage but also corresponds to the position change S. If the sampling interval of the linear stage is h and the position change by rotation is S_j, the position x on the surface corresponding to the connected angle A_i is calculated as Eq. 3:

$$x = ih + \sum S_j \tag{3}$$

If the rotated angle α, the distance D between the rotation centre are known, the position change S is calculated as Eq. 4.

$$S_j = 2D\sin\left(\frac{\alpha_j}{2}\right) \tag{4}$$

As a result, the angle is connected with proposed method as shown in Fig. 5.

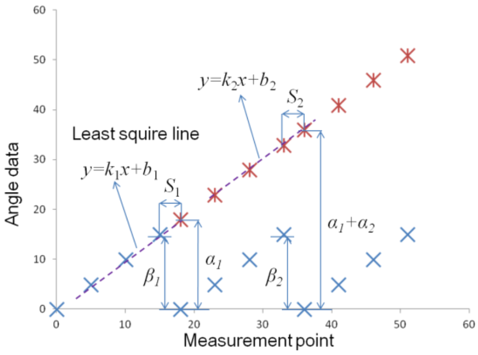

Fig. 5 Connection of angle data

With the connected angle data and the according position, the profile of the surface is calculated by numerical integration as shown in Eq. 5.

$$f_0 = 0$$
$$f_x = f_{x-1} + \frac{h_x\left(f'_{x-1} + f'_x\right)}{2} \qquad (5)$$
$$f'_x = \tan\left(A_{ij}\right)$$

Where f_x is the profile data that make the first profile data as zero. f'_x is the differential of the profile.

With the proposed data processing method, the profile data of surfaces under measurement is calculated with interrupted raw angle data detected by autocollimator.

4. EXPERIMENT

To verify the principle of proposed method, an experimental setup is built for of axial symmetric surfaces measurement as shown in Fig. 6.

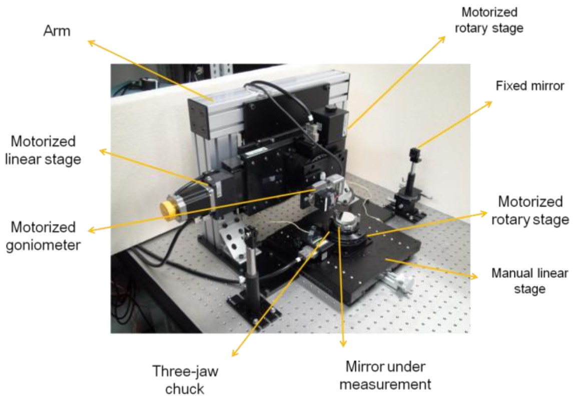

Fig. 6 Three dimension measurement setup

In this setup, a linear stage is fixed on a stage arm for linear scanning of the sample surface. On it a rotation stage is fixed. An autocollimator with measuring range of the autocollimator ± 100 arc-sec is fixed on the rotation stage. A motorized goniometer is fixed between the autocollimator and the rotation stage to adjust the angle of autocollimator. The sample surface is fixed horizontally in a three-jaw chuck. And under the chuck there is another rotation stage, which is used for the secondary translation of sample surface so that three dimensional profile data is measurable.

Before the measurement of sample surfaces, the pitch angle of the linear stage is measured. As shown in Fig. 7,

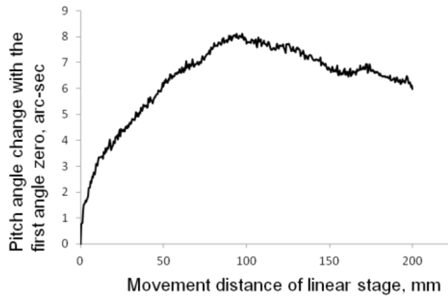

Fig. 7 pitch angle error of linear stage

The repeated measurement experiments of the pitch angle are done and the standard deviation of 10 times measurement is shown as Fig. 8. The mean standard deviation is 0.3 arc-sec.

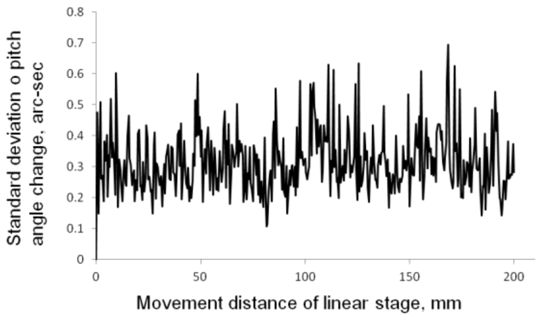

Fig. 8 Repeatability of linear stage pitch angle

A concave mirror with diameter of 50 mm is then measured with the setup. One line of the mirror near the centre is scanned. To avoid the measured angle exceeding the measuring range of the autocollimator, when the detected angle is more than 40 arc-sec, the rotation stage rotated 80 arc-sec back. Other measurement parameters are shown in Table 1.

Table 1 Measurement parameters

Linear stage scanning distance, mm	40
Linear stage scanning interval, mm	0.5
Distance from rotation centre of rotation stage to sample surface, mm	100
Measurement time for once scanning, min	3.5

The measured raw angle data is shown in Fig. 9. Because the measuring range of the autocollimator is smaller than the slope change of the concave mirror, the rotation stage is rotated by 20 times in one line scanning.

With the raw angle data and the pitch angle data of linear stage, the connected angle and the according position on the mirror is calculated with proposed data processing method introduced above. The connected angle data is shown in Fig. 10.

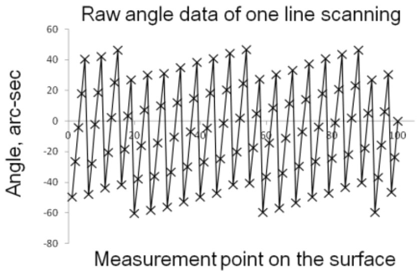

Fig. 9 Raw angle data of one line scanning

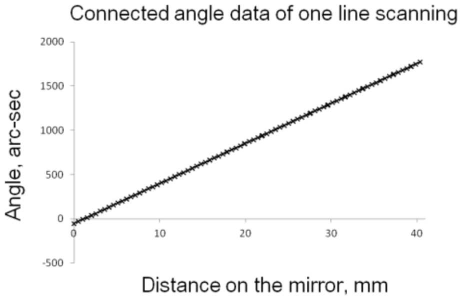

Fig. 10 Connected angle data of one line scanning

The measured slope change of the concave mirror is 1824.5 arc-sec. In view of the measuring range of the autocollimator, it is proved that our proposed method is able to enlarge the measuring range of the autocollimator.

The profile is then calculated with numerical integration from connected angle data as shown in Fig. 11.

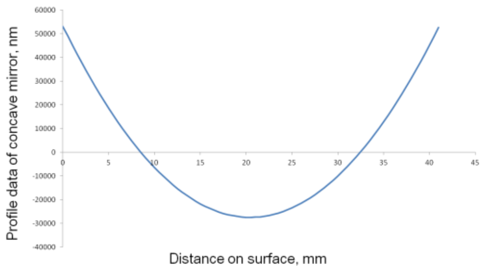

Fig. 11 Measured profile of concave mirror

One line scanning measurement is then repeated for 11 times to see the measurement repeatability. The deviation of of 11 times measured profile is shown in Fig. 12. The distribution of standard deviation is shown in Fig. 13. The mean of the standard deviation is 3.7 nm.

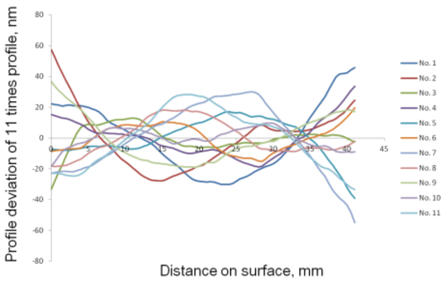

Fig. 12 Profile deviation of 15 times measurement result

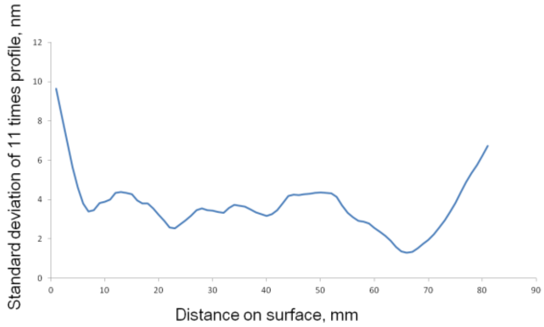

Fig. 13 Standard deviation of 11 times measurement result

5. CONCLUSION

A new method is proposed based on deflectometry method for the measurement of large aspheric optical surfaces with large slope change. An experimental setup is built to verify the basic principle of proposed method. Experiment result shows that proposed method successfully enlarged the measuring range of the autocollimator. Furthermore, repeated experiments result shows that the measurement repeatability is less than 5 nm when measuring normal size mirror with large slope change. In future work, measurement experiment of aspheric surfaces will be done and the absolute accuracy will be investigated.

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