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Profile Measurement of Large Aspheric Optical Surface by Scanning Deflectometry with Rotatable Optical Devices - Error Analysis and Pre-experiment-

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Abstract

Large aspheric mirrors with diameter over 300 millimeters with high surface accuracy are wildly used in many areas such as astronomical telescopes. Interferometers are widely used in profile measurement of optical flat and sphere. However, standard reference aspheric surface which is necessary for this method is difficult to make. Scanning defletometry based on ESAD (Extended Shear Angle Difference) is used to measure ultra-precise large near-flat and slight curved optical surface with the accuracy of sub-nanometer. However, it is not possible for it to measure aspheric surface because of the limitation of the measuring range of autocollimators. We proposed a new measuring method to scan the surface of a large aspheric optical surface using autocollimator with rotatable optical devices fixed on linear motion stage. To eliminate the influence of the pitching error of the scanning stage, we use two mirrors reflecting laser comes from autocollimator, which have the same effect with a pentaprism used in ESAD. To enlarge the measuring range of the autocollimator, we use a rotatable mirror to fit the changes of the slope of the mirror surface under measurement. The error analysis of the method is done. Measurement of an optical flat mirror and a sphere mirror with diameter of 50 mm and biggest slope of 6000 arc-second are done. The rotatable optical devices that we designed are proved effective on eliminating the pitching error of the moving stage.

1. Introduction

Aspheric mirrors and lenses are used more popular in optical industry because they can improve correction of aberrations [1]. These aspheric surfaces are becoming more precise, and scale of them becomes to be larger than hundreds of millimeters. So, profile measurement of large aspheric surface becomes an important subject. However, there is no measurement machine that can measure an aspheric surface with diameter of hundreds of millimeters and with slope over 10 arc-degrees with precision of 10 nm.

Interferometers have high efficiency when measuring optical surfaces. However it faces difficulties when the aspheric surface has a large departure of slope from the best fitting reference surface. Multi-probe method has low efficiency but can easily enlarge the horizontal measuring range. However, the problem of difference between sensors is remained unsolved for multi-probe method.

Scanning defletometary based on ESAD (Extended Shear Angle Difference) is used to measure ultra-precise near-flat and slight curved optical surface with the accuracy of sub-nanometer [2]. However, this method cannot measure surfaces with large slope that is larger than the measuring range of the autocollimator.

We proposed a new method using a rotatable mirror and a fixed mirror instead of the pentaprism in ESAD. The measuring range is enlarged and the pitching error of the scanning stage can also be eliminated by the fixed mirror and rotatable mirror. Error analysis is done, experimental devices are designed and the pre-experiment is done.

2. Principle

The principle of the method is shown as Fig. 1. Mirror under measurement is fixed. One rotatable mirror and one fixed mirror are assembled with moving stage. Laser come from autocollimator is reflected twice by these two mirrors and then reflected by the concave mirror under measurement. After reflecting by those two mirrors on the moving stage, laser goes back to the autocollimator. Then the reflection angle of the concave surface is measured by autocollimator. The moving stage moves to scan the whole surface of the concave mirror. And when the reflection angle becomes close to the measuring range of the autocollimator, the rotatable mirror turns a certain angle to fit the slope of the concave mirror and continue scanning. The angle of the concave mirror on the line paralleled with the moving stage is known by scanning once. Then turn a certain angle of the concave mirror revolving around the principal axis of the concave mirror and continue to scan.

The angle data measured by autocollimator is transformed to derivation, and then the profile data of the concave mirror is known by the formals written as Eq. (1).

$$
\begin{aligned}
& f_0 = 0 \\
& f_{i+1} = f_i + \frac{h}{2}\left(f_i' + f_{i+1}'\right) \quad i = 0,1,\ldots,n-1
\end{aligned}
\tag{1}
$$

Where f_i is the placement of point i on the concave mirror. f'_i means the derivation of point i.

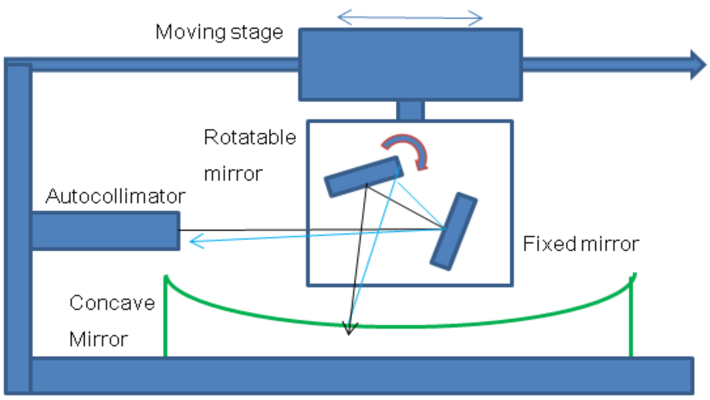

Fig. 1 Angle measurement system with one rotatable mirror and one fixed mirror

3. Error analysis

Before the Pre-experiment, error analysis is done to check what kind of factors affect the measurement result and how they do it.

The angle error is caused by error of autocollimator E_s and the error caused by the offset of measuring point of the mirror under measurement Δx which is defined as E_x.

There is no difference between measuring spherical surface and aspheric surface by the method we proposed, we take spherical surface example for error analysis. The function of the spherical surface is defined as Eq. (2). And the second derivative is calculated as Eq. (3).

$$f = \sqrt{R^2 - x^2} \tag{2}$$

$$f'' = -\frac{R^2}{\left(R^2 - x^2\right)^{\frac{3}{2}}} \tag{3}$$

When x =0, $E_x = -\Delta x / R$.

Because E_s and E_x is independent and both of them is supposed to be random error, they are combined as E_c shown as Eq. (4).

$$E_c = \sqrt{E_s^2 + E_x^2} \qquad (4)$$

The uncertainty of profile measured by this method is

$$\sigma_f = \sqrt{N} h E_c = \sqrt{hL} E_c \qquad (5)$$

Where N is number of sampling data, h is sampling interval and L is the length of the mirror under measurement [3].

For example, if uncertainty of autocollimator is 0.1 arc-second (about 0.5 μrad), the position accuracy of scanning stage Δx is 1μm, the length of the mirror is 300 mm, the sampling interval h is 0.5 mm, R is 1000 mm, the uncertainty of profile will be about 10 nm.

The result of the error analysis shows that the method we proposed can get high precision of dozens of nanometers when the error factors are controlled well.

4. Pre-experiment

4.1 Pre-experiment devices

Pre-experiments are done to verify the method we proposed. As the pitching angle of scanning stage will affect the angle data of the mirror, the pitching and yawing data is measured by an autocollimator before measuring the profile of mirrors. Photograph of pre-experiment is shown in Fig. 2. Parameters of key devices are shown in Table 1.

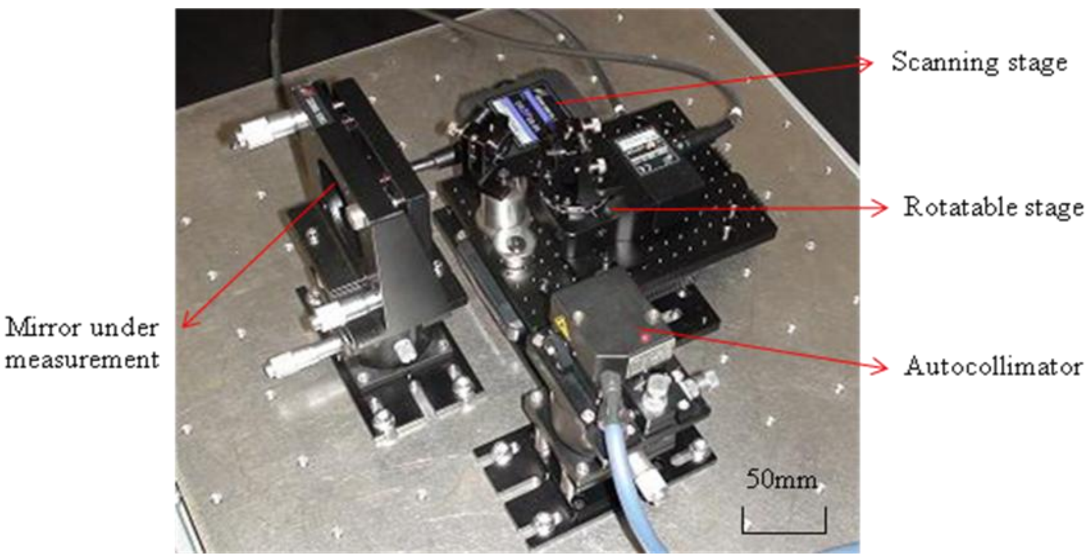

Fig. 2 Experimental set up for profile measurement

Table 1 Parameter of key device for pre-experiment

Name of the device	Moving/measuring rage	Repeatability	Resolution
Autocollimator	200 arc-second	unknown	0.01 arc-second
Linear stage	35 mm	3 μm	25 nm
Rotatable stage	360 degree	0.02 degree	0.225 arc-second

4.2 Profile measurement of flat mirror

The pitching data is measured for four times by autocollimator shown in Fig. 3. The data of pitching angle can be used to compensate the measurement data of mirrors.

A flat mirror with diameter of 50 mm is measured by scanning in one line. The moving range of the scanning stage is 35 mm, so only part of the mirror is measured. Because the flatness of the mirror is small, the effect by pitching of scanning stage is large. The profile data compensated with the angle data of scanning stage is shown in Fig. 4(a).

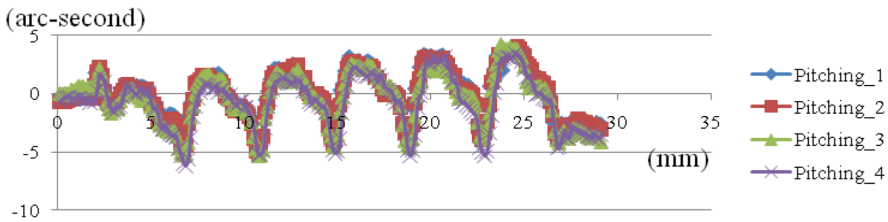

Fig. 3 Pitching data of scanning stage

To eliminate the effect of pitching angle of scanning stage, another mirror is set on the scanning stage to make one more time reflection of laser from autocollimator (shown as Fig. 2 (b)). These two mirrors together have the same effect with a pentaprism. Profile of flat mirror is shown in Fig. 4 (b).

The result shows that data measured by two-mirrors-reflecting is better than that by one mirror reflecting.

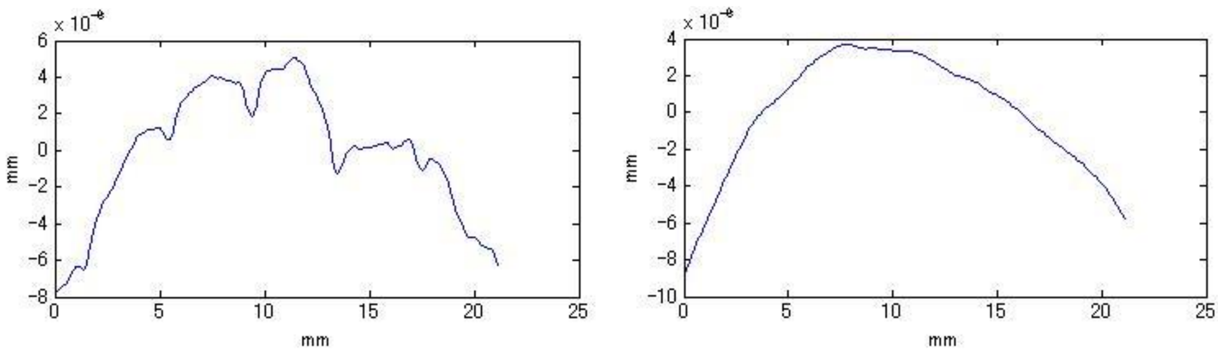

Fig. 4 Profile data of flat mirror: (a) by one reflecting mirror, (b) two reflecting mirrors

4.3 Profile measurement of concave mirror

Concave mirror with diameter of 50 mm and with curvature radium of 5000 mm is measured as the principle shown in Fig.1. Measurement is done for 6 times. Data is shown in Fig. 5 (a).

Because the angle data is not continuous, we connect the angle data. The measure point after each rotation of rotatable mirror is considered to be the same point before rotation. In other words, the lost part caused by rotation is not considered. And the connected data is shown in Fig. 5 (b).

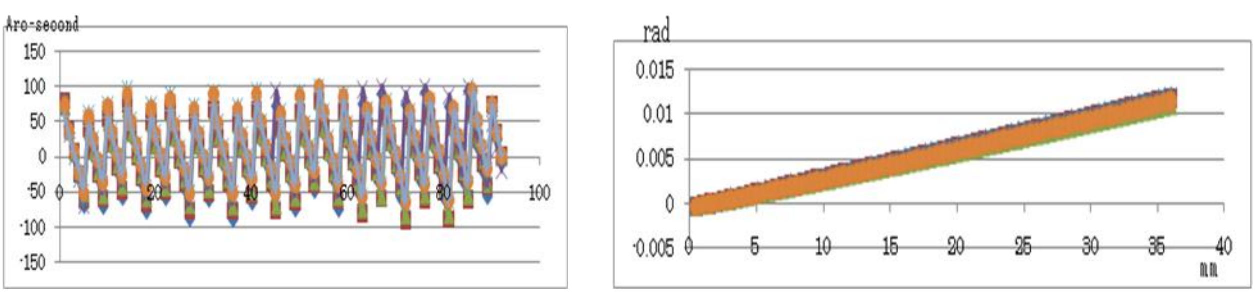

Fig. 5 (a)Angle data of concave mirror (b) Connected angle data of concave mirror

Then the connected angle data is used to calculate the profile data by Eq. 1. The profile data is shown as Fig. 6.

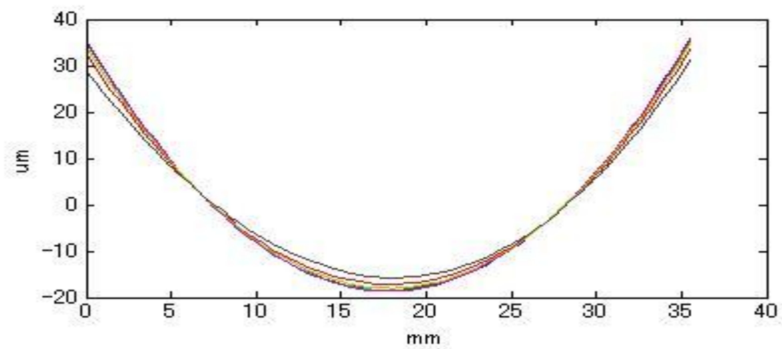

Fig. 6 Profile data of concave mirror from calculation of angle data

5. Conclusion

A new method by scanning deflectometry with rotatable optical devices for measuring aspheric method is proposed and the error analysis and pre-experiments are done. The system designed is proved that it can eliminate effect of pitching angle of scanning stage. Profile of concave mirror with slope of 2500 arc-second is measured by an autocollimator with measuring range of 200 arc-second. The measuring range is proved to be enlarged by our new method.

6. Acknowledgement

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