PROFILE MEASUREMENT OF LARGE ASPHERIC OPTICAL SURFACE BY SCANNING DEFLECTOMETRY WITH ROTATABLE MIRROR -METHOD FOR ENLARGING MEASURING RANGE OF AUTOCOLLIMATOR-

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Abstract

Interferometers are widely used for measuring large reflecting flat surfaces and spherical surfaces because of its high accuracy and high efficiency. Because interferometry needs standard reference surface for measurement, when measuring a large aspheric surface it needs null lens or hologram to make an aspheric wave front. However, if the perfect profile of the aspheric surface is not known before test, interferometry cannot be used to measure. When measuring a large flat, deflectometry is also proposed and proved to have high precision of sub-nanometers. However, it cannot be used because of the limit of the measuring range of the autocollimator. We proposed a new scanning deflectometry method using an autocollimator and a rotatable mirror fixed on a scanning stage. The rotatable mirror and a fixed mirror are supposed to have the same function as a pentagon prism which can eliminate the pitching angle error of the scanning stage as it moves. We scan slope of the aspheric mirror by autocollimator, and when the angle becomes close to exceeding the measureable range of the autocollimator, the rotatable mirror is turned a certain angle to fit the slope of the aspheric mirror and continue scanning. The error analysis of the method is done, and the result show that if the condition is well controlled the uncertainty of this method is 10nm. Pre-experiments is done, which proved that the rotatable scanning mechanism is able to eliminate pitching error of the scanning stage.

Key words: Profile measurement, aspheric optical surface, scanning deflectometry, rotatable mirror, measuring range enlargement

1. Introduction

Large aspheric mirrors and lens with high precision of several hundred nanometers are used on modern industry, such as mirrors for reflecting telescopes and brightest x-ray beam reflecting mirrors. However, the measurement of such large aspheric mirror is still faces many problems.

Interferometic methods are widely used when measuring optical flat and spherical surface because of their high efficiency and high accuracy. And when the departure from the fitting sphere is too large, accessories such as null lenses and computer generated holograms (CGH) are necessary to make an aspheric wavefront [1]. However, this kind of methods can measure the aspheric surface only when the perfect surface is known before the measurement. And surfaces such as cylinder surface cannot be measured by this kind of methods.

Scanning deflectometry method with a pentagon prism is proposed to measure flatness of a large optical flat shown in Fig.1 [2]. Because of the pentagon prism, the pitching error of the scanning stage is eliminated while moving. As a result, the angle change of the optical surface is measured by autocollimator accurately. Experiments show that the uncertainty of this method is less than sub-nanometer when measuring large flats with diameter of 500 mm with a high precision autocollimator and pentagon prism fixed on the scanning stage. However, this method cannot be used to measure not flat mirror because the measuring range of the autocollimator is not more than one arc-degree.

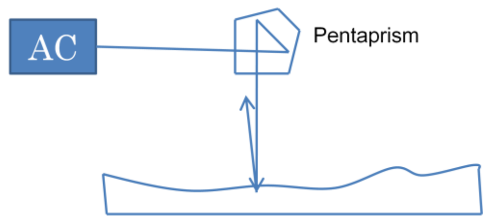

Fig.1 Principle of scanning deflectometry method with pentagon prism

We proposed a new method based on scanning deflectometry for measuring large aspheric optical surface. The method we proposed also uses high precision autocollimator and scanning stage to scan the angle change of the optical surface. Instead of the pentaprism two reflecting mirrors are fixed on the scanning stage to eliminate the pitching error of the scanning stage. And one of the mirrors is a rotatable mirror driven by a rotation motorized stage. Therefore the measuring range of the precision autocollimator is enlarged and the new scanning deflectometry method can be used to measure large surface with large slope including large aspheric surface.

In this paper, the principle of the method we proposed is introduced, the error analysis is done and pre-experiments are done.

2. Principle

The basic principle shown in Fig.2 is almost the same with other scanning deflectometry methods. An autocollimator head is fixed on the flame. Laser from the autocollimator head is reflected twice by the mirrors fixed on the scanning stage and then reflected from the mirror under measurement. After reflecting twice again by the mirrors on the stage the laser returns to the autocollimator head. Then the angle of this point is detected by autocollimator. Movie the stage and angle change is detected. When the detected angle becomes close to exceeding the measuring range of the autocollimator, we turn the rotatable mirror a certain angle to fit the angle of the mirror surface by rotation stage and continue to scan. Finally, the angle change of one line of the mirror is detected.

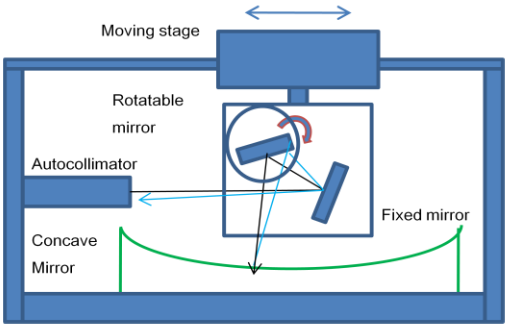

Fig.2 Principle of scanning deflectometry method with rotatable mirror

Because of the rotation of the mirror, the angle detected by autocollimator is not continuous but interrupted as shown in Fig.3. To connect the angle data we have to know the missed distance on caused by rotation. If the turned angle α and the distance between the rotation mirror D and the mirror under measurement should is known, the missed distance S can be calculated as $\alpha \times D$.

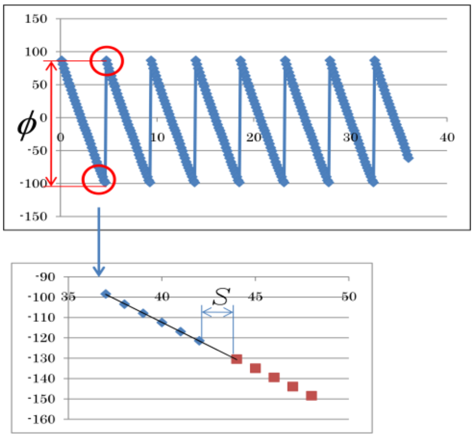

Fig.3 Simulation of angle data measured by autocollimator

The angle turned is controlled by controller of the rotation stage. However, the accuracy is not good enough when the angle is tens of arc-seconds. Fortunately, because the turned angle is small, near the mirror under measurement is similar to flat mirror at that point. As a result, the angle can be estimated by the difference between the angle before rotation and after rotation ϕ that is detected by autocollimator. As a result, the missed distance S can be calculated as $\phi \times D$.

Then the connected angle data is calculated to get profile data by integral. The profile data of the concave mirror is known by the formals written as Eq. (1).

$$f_0 = 0,\ f_{i+1} = f_i + \frac{h}{2} * (f_i' + f_{i+1}'); \quad (i = 0, 1, \ldots, n-1) \tag{1}$$

f_0 is the start point of the profile; f_i is the displacement data of point i; h is the interval of scanning.

3. Error analysis

We did the error analysis to check what kind of factors affect the measurement result and how they do it.

The uncertainty of the displacement data E_d comes from the angle uncertainty E_a measured by autocollimator which will affect f_i. 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 $\triangle x$ 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).

$$x^2 + y^2 = R^2 \tag{2}$$

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

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

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).

$$E_c = \sqrt{E_s^{\ 2} + E_x^{\ 2}} \tag{4}$$

The uncertainty of profile measured by this method is

$$\sigma_f = \sqrt{N} h E_c = \sqrt{hL} E_c \tag{5}$$

N is number of sampling data, h is sampling interval and

L is the length of the mirror under measurement.

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 10 nanometers when the error factors are controlled well.

4. Pre-experiment

4.1 Measurement of pitching of scanning stage

Primary 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 experiment is shown in Fig. 4 (a).

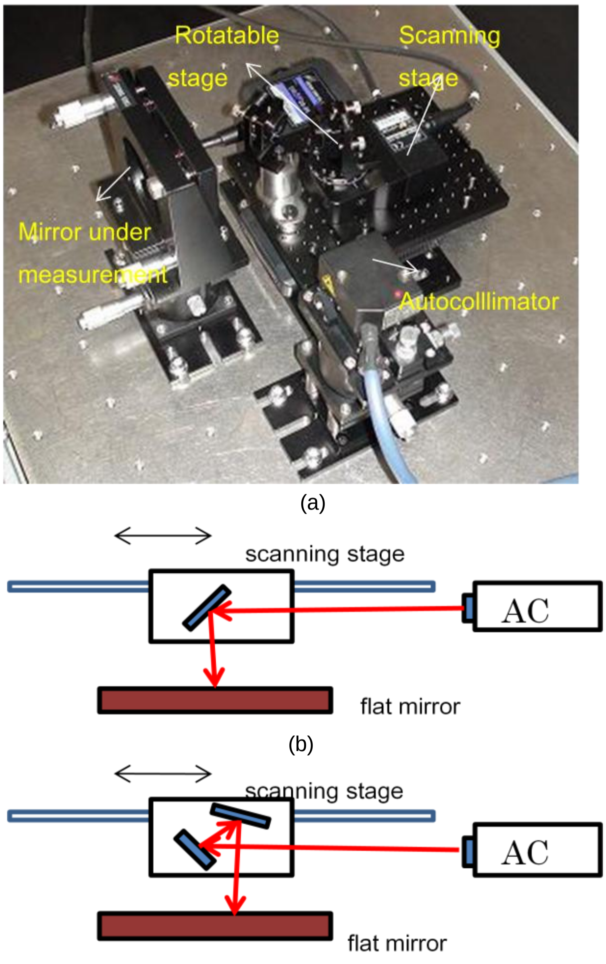

Fig. 4 Experimental set up for profile measurement:
(a) Photograph of pre-experiment equipment
(b) Scanning by one reflecting mirror
(c) Scanning by two reflecting mirrors

The pitching data is shown in Fig. 5. The data shows that the scanning stage has stable pitching angle with good repeatability when scanning. So the data of pitching angle can be used to compensate the measurement data of mirrors.

4.2 Profile measurement of flat mirror

After the measurement of pitching and yawing of scanning stage, the profile of one flat mirror with surface precision of $\lambda/10$ and diameter of 50 mm is measured by scanning in one line (λ = 632.8 nm) as shown in Fig. 4 (b). 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 result of the angle data of flat mirror is compensated with the angle data of scanning stage (shown in Fig. 6(a)).

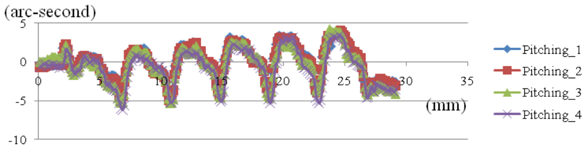

Fig. 5 Pitching error of scanning stage

By comparing with the least squares line, the straightness of the line transformed from the angle data is 12.8 nm which is than $\lambda/10$. It shows that although the compensation makes the result better, the effect from pitching of scanning stage is not eliminated completely.

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. 4 (c)). These two mirrors together have the same effect with a pentaprism. Profile of flat mirror calculated by angle data by this method is shown in Fig. 6 (b).

The profile calculated from angle data measured by two-mirror-reflecting is better than that by one mirror reflecting.

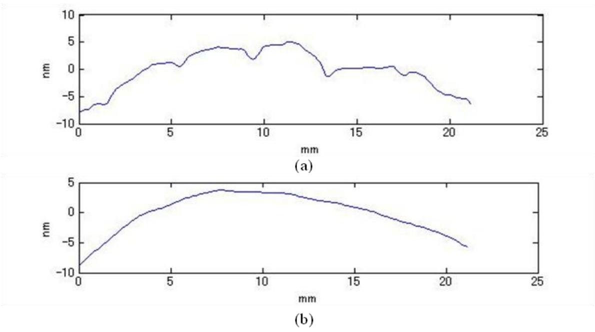

Fig. 6 Profile data of flat mirror:
(a) One reflecting mirror, (b) Two reflecting mirrors

5. Conclusion

We proposed a new scanning deflectometry method with rotatable mirror to measure the profile of large aspheric optical surface over 300 mm. The error analysis shows that the method we proposed is able to measure a large surface over 300 mm with uncertainty of 10 nm. And the result of pre-experiments verified that as the laser is reflected twice by two mirrors, the pitching error of the scanning stage is eliminated.

6. Acknowledgement

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Reference

[1] J. H. Burge, Applications of computer-generated holograms for interferometric measurement of large aspheric optics, Page258-269, SPIE Vol. 2576.
[2] Ralf D Geckeler, Optimal use of pentaprisms in highly accurate deflectometric scanning, 115–125, Meas. Sci. Technol. 18 (2007).
[3] Muzheng Xiao, Satomi Jujo, Satoru Takahashi, Kiyoshi Takamasu, Nanometer Profile Measurement of Large Aspheric Surface (2nd report) -Simulation of Error Analysis and Experimental Verification of Measuring Method Using Autocollimator and Rotatable Mirror-, Page 371-372, Collected papers of 2010 JSPE Spring Meeting.
[4] Muzheng Xiao, Satomi Jujo, Satoru Takahashi, Kiyoshi Takamasu, Nanometer Profile Measurement of Large Aspheric Surface (1st report) -Evaluation on Profile Measurement Methods-, Page 703-704, Collected paper of 2009 JSPE Autumn Meeting.