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# DEFLECTOMETRIC PROFILER WITH SMALL BEAM SIZE USING A COMMERCIALLY AVAILABLE AUTOCOLLIMATOR

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**Abstract**:

The special resolution of the angle-based deflectometric surface profiler has been improved by introducing a novel null instrument. Proposed null instrument is simple, inexpensive, and has fast response time. High accuracy flatness measurement for low reflective surface has been successfully demonstrated with 1 mm laser beam spot size. The repeatability of the surface form measurement is better than ±0.6 nm.

**Keywords**: flatness, metrological instrumentation, surface form measurement, deflectometry, autocollimator

## 1. INTRODUCTION

Demand for the high accuracy and wide area surface form (flatness) measurement is becoming increasing higher owing to the progress of the industry and research filed. The Fizeau interferometer has been widely adopted not only for use in industrial applications but also as the national-standard class flatness measurement instrument. In Fizeau interferometry, a comparison is made between a reference flat and a measurement flat. In order to obtain an accurate absolute profile of the measurement flat, the absolute profile of the reference flat must be known to high accuracy. To determine the absolute profile of the reference flat, three-flat test is typically utilized. The absolute topography with many radial lines is obtained as the number of rotational steps in three-flat test. Flatness measurement uncertainly with nanometer level can be achieved by use of three-flat test. To improve this uncertainty, the gravity deformation of specimens is one of the intrinsic problems in horizontally oriented setting. The value of gravity deformation cannot be directly determined by three-flat test. In addition, measurement of large size specimen, such as a bar mirror with longer than 1 meter is not suitable for Fizeau interferometry.

On the other hand, deflectometry with angle-based measurement has the potential fora sub-nanometer level uncertainty and large size profile measurement longer than 1 meter. In the deflectometric system, local slope distribution of the specimen is measured and surface profile is calculated as the integration of the measured local slope distribution. High accuracy of the surface profile determination is achieved by high accuracy angle measurement. Large size measurement is guaranteed by the moving range of the local angle measurement system.

There are two types of angle-based deflectometric surface profile measurement system. In one deflectometric system, the local slope distribution is measured by a laser beam and a beam angle measurement system, which is constructed of a lens and a two dimensional beam position detector, such as CCD camera [2, 3]. A long trace profiler (LTP) is well used in synchrotron radiation facilities for surface profile measurement of X-ray optics. In LTP system, although small beam size angle measurement system, whose diameter is few mm, can be realized, in-situ calibration of angle measurement system is required for achieving high accuracy absolute surface form measurement.

In the other deflectometric system, a commercially available autocollimator is directly used for the measurement of the local slope of the surface of the specimen [4-6]. In this method, the beam from the autocollimator is scanned by the movement of a pentagon mirror. The beam spot size on the specimen is reduced by an aperture, which is located just before the surface. Accuracies of local slope measurements by use of the commercially available autocollimators have been evaluated with the aperture in detail [7, 8] and consequently high accuracy surface profile measurements have been achieved.

However, the aperture size is usually limited to be larger than several mm in this direct measurement method. Especially for the low reflectivity surface, such as for glass surface, realizing high lateral resolution measurement is difficult because of the limited performance of the commercially available autocollimator. In order to overcome this problem, Schulz et al. have been proposed the use of an additional null instrument [9-11]. In the proposed method, the setting angle of the specimen is adjusted so as to keep a constant reflection angle by means of the null instrument, which uses an additional autocollimator. The local slope distribution is converted to the change in the setting angle of the specimen during the beam scanning. The change in the setting angle of the specimen is measured by the other autocollimator with large aperture and fixed measurement distance. Although the beam spot size on the measurement surface can be small by the null instrument, the measuring time is enlarged and the noise level is increased by a factor of $\sqrt{2}$ due to the use of two autocollimator. In ref 11, typical measurement time for each measuring point is about 10 s. In addition, needless to say, this proposed system becomes expensive due to the use of two "high end" type autocollimators.

In this paper, we propose a novel null instrument system to improve the lateral resolution of the angle based scanning deflectometric profiler (SDP). Proposed null instrument system is simple, inexpensive, and without the autocollimator, and has fast response time. Totally, only one autocollimator is used in the proposed measurement system.

## 2. SETUP AND THEORY

### 2.1 Experimental setup

Figure 1 shows the experimental setup of the proposed SDP, which uses a null instrument. A laser output originating from a laser diode (LD) with a diameter of approximately 1.08 mm ($1/e^2$) is used as the beam for measuring the local angle of the surface under test (SUT). The wavelength of the LD is approximately 658 nm. Laser beam illumination of the SUT is achieved through a half mirror and a pentagon mirror. The laser beam spot on the SUT is mechanically scanned using the pentagon mirror. The pentagon mirror is a key device for removing the motion error due to scanning. Normally, a pentagon mirror or a prism with an angle of 45 degrees is used in the deflectometric system. In the setup of the present study, a pentagon mirror with an angle of 135 degrees is adopted. Technically, there is no difference between the 45-degree and 135-degree mirrors. The primary reason for adopting a pentagon mirror with an angle of 135 degrees is that such a mirror can be produced more easily and with high accuracy. The solid-angle accuracy of the 135-degree pentagon mirror is better than 1 arcsec.

Part of the laser beam reflected from the SUT is divided by a half mirror and introduced to the proposed null instrument. The null instrument is constructed of a prism type reflection mirror on the rotation stage, a lens, and a quadrant cell photodetector (QPD), as shown in Fig. 1. There are two reflection plane on the prism and high reflection coatings are added on the reflection plane for the laser beam and autocollimator, respectively. The QPD is located at the focal position of the lens; consequently, the beam position on the QPD is changed by changing the local slope angle of the SUT as a result of the mechanical scanning. In the proposed method, the angle of the reflection mirror is adjusted so that the beam position on the QPD always remains on the center line of the vertical direction of the QPD. The local slope distribution of the SUT is translated to the change in the rotation angle of the reflection mirror. The change in the rotation angle of the reflection mirror is directly measured by a commercially available autocollimator having a large beam size. The measurement distance between the autocollimator and the prism type mirror can be short and fixed. A commercially available ELCOMAT 3000 (MÖLLER-WEDEL OPTICAL GmbH) autocollimator is used in the experimental setup.

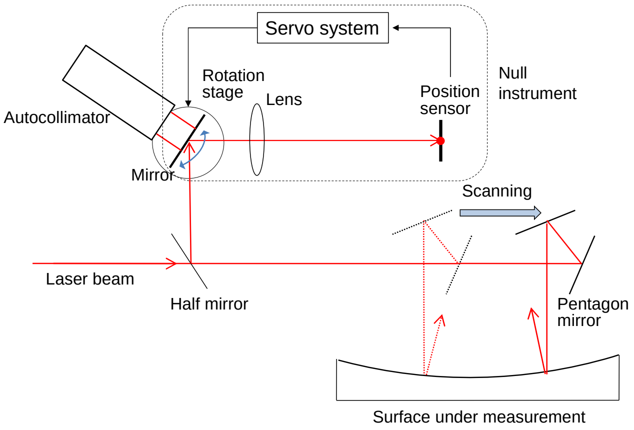

Fig. 1: Experimental setup of the proposed scanning deflectometric profiler (SDP).

In principle, the accuracy and lateral resolution of deflectometry using the commercially available autocollimator can be improved by installing the null instrument. In the method proposed in Refs. 9 through 11, the angle of the specimen, which might be large and heavy, is adjusted using a piezoelectric transducer (PZT) to maintain the null angle. In Ref. 12, in order to enlarge the angle measurement range, a rotating stage is installed for adjusting the angle of the measurement beam from the autocollimator. On the other hand, the angles of the specimen and the measurement beam used to illuminate the SUT are fixed in the proposed method. The angle of the small mirror is adjusted so that more accurate and high-speed angle control is expected. In the experimental setup of the null instrument, the rotation stage is controlled by a PZT. The range of rotation and angular motion error of the rotation stage are approximately 1,000 arcsec and 1.5 arcsec, respectively, for a rotation of 1,000 arcsec, which is negligible for flatness measurement. The focal length of the lens is 1 m. The bandwidth of the QPD is 100 kHz, and the measurement range of the beam position by the QPD corresponds to an angular change of approximately 80 arcsec.

### 2.2 Surface form calculation

The surface profile $F(x_i)$ of the specimen is obtained by integrating the local slope angles as follows:

$$f(x_i) = 0 \quad (i = 1), \tag{1}$$

$$f(x_i) = f(x_{i-1}) + (x_i - x_{i-1})\{f'(x_{i-1}) + f'(x_i)\}/2 \quad (i = 2, 3, \ldots N). \tag{2}$$

where $i$ is the measurement number, N is the total number of measurement points, $f(x_i)$ is a profile, $f'(x_i)$ is a measured local slope angle, and $x_i$ is the measurement position. The numerical integration of Eqs. (1) and (2) is calculated as the first measurement position $f(x_1)$ is to be zero. Then, the least square line $g(x_i)$ is calculated from the profile $f(x_i)$ as follows:

$$g(x_i) = a_0 x_i + b. \tag{3}$$

The DC component of the measured local slope distribution $f'(x_i)$ corresponds to $a_0$. By subtracting $g(x_i)$ from $f(x_i)$, we can obtain the final profile $F(x_i)$ as follows:

$$F(x_i) = f(x_i) - g(x_i). \tag{4}$$

### 2.3 Alignment and stability

In order to obtain accurate surface profile data and minimize the error due to mechanical scanning, the axis of the measurement laser beam, the pentagon mirror, and the axis of the mechanical scan must be correctly aligned [13]. In order to perform the alignment method described in Ref. 13, before measurement, the measurement beam of the ELCOMAT 3000 is introduced to the SUT through the half mirror and the pentagon mirror. Then, the axis of the

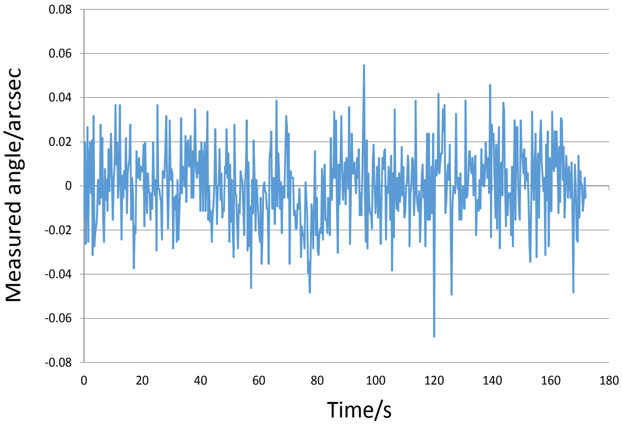

Fig. 2: Short-term stability of the output of the ELCOMAT 3000 when the null instrument was activated and the laser beam was used to illuminate a fixed point on the SUT.

ELCOMAT 3000, the pentagon mirror, and the axis of the mechanical scan are aligned as described in Ref. 13. Next, the angle of the laser beam of the LD is adjusted to be parallel to the measurement beam of the ELCOMAT 3000, and thus correct alignment can be realized.

Figure 2 shows the short-term stability of the output of the ELCOMAT 3000 when the null instrument was activated and the laser beam was used to illuminate a fixed point on the SUT, which was glass. The sampling rate of the ELCOMAT 3000 is 25 Hz, and the angle data shown in Fig. 2 was taken every 300 ms. The standard deviation of the measured data is approximately 0.017 arcsec, which is approximately the same as that when the null instrument was not activated. Therefore, the short-term stability (noise level) of the proposed system is approximately determined by the noise level of the ELCOMAT 3000.

## 3. MEASUREMENT RESULTS

In order to demonstrate the performance of the proposed SDP, a ceramic surface (low-reflectivity surface) with small unevenness was measured. In order to avoid the influence of long-term drift, we adopted a measurement strategy in which the measurement was performed in four directions: forward, backward, backward, and forward [14]. Figure 3 shows the measured local slope distributions when the scanning step $\Delta x = x_i - x_{i-1}$ was 0.25 mm. The measurement diameter was 70 mm. At each measuring point, 25 angle data were averaged, and the total measurement time for each measurement point was approximately 2.5 s. In Fig. 3, there are 10 local slope distributions, i.e., the total number of line measurements was 40. The measured range of the autocollimator was approximately 1.8 arcsec. The profile was calculated by integrating the local slope distribution obtained by averaging the four measurements. Figure 4 shows the calculated profiles for scanning steps of 0.25 mm. The PV value of the surface profile was approximately 40 nm. Figure 5 shows the difference curves with respect to the average profile. The repeatability was better than ±0.8 nm.

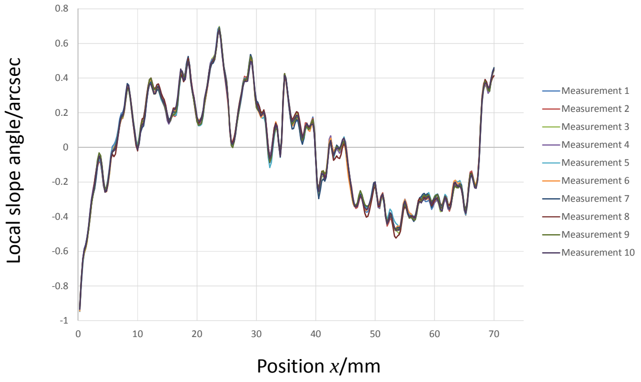

Fig. 3: Measured local angle slope distributions of the glass surface.

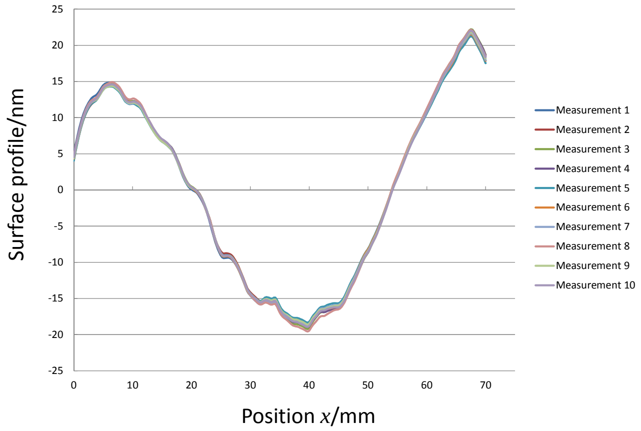

Fig. 4: Measured surface profiles of the ceramic surface.

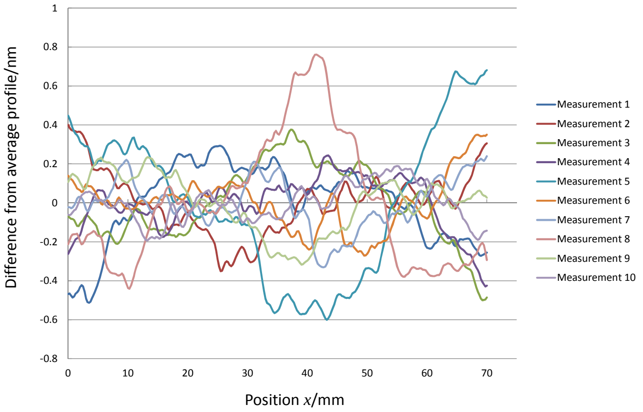

Fig. 5: Difference curves with respect to the average profile shown in Fig. 4.

In addition to the surface profile measurement results shown in Fig. 4, a ceramic surface (low-reflectivity surface) with smooth and larger deformation was also measured. In this measurement, we also adopted a measurement strategy in which the measurement was performed in four directions. Figure 6 shows the measured surface profile when the scanning step $\Delta x$ was 0.25 mm. The measurement diameter was 70 mm and 25 angle data were averaged at each measuring point. In Fig. 6, there are 10 surface profiles. The measured range of the autocollimator was approximately 4.8 arcsec and the PV value of the surface profile was

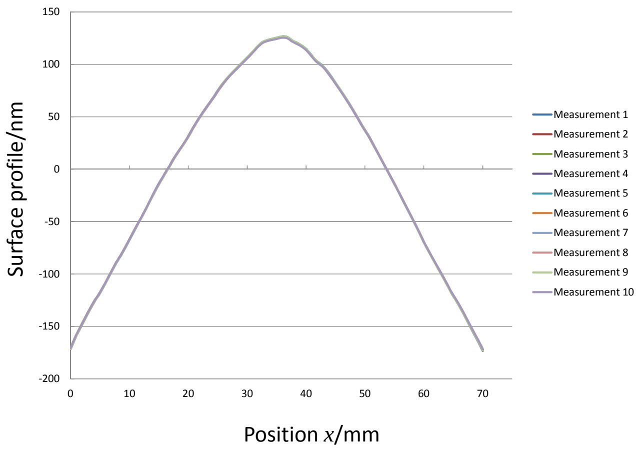

Fig. 6: Measured surface profiles of the ceramic surface with large deformation.

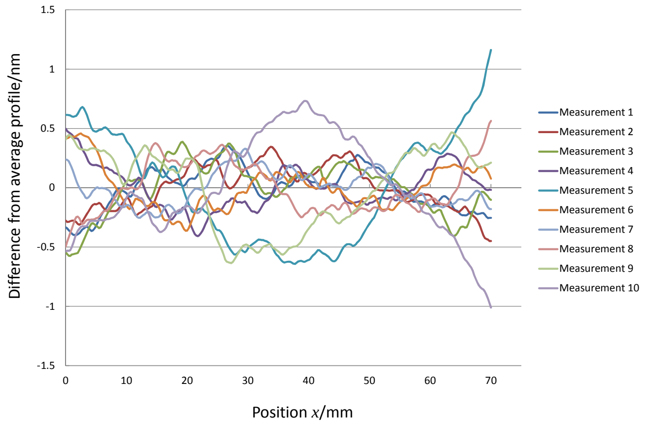

Fig. 7: Difference curves with respect to the average profile shown in Fig. 6.

approximately 300 nm. Figure 7 shows the difference curves with respect to the average profile. The repeatability was also better than ±1 nm.

## 4. CONCLUSION

In conclusion, we developed a null instrument in order to improve the lateral resolution of angle-based deflectometry using a commercially available autocollimator. The proposed null instrument system is simple, inexpensive, and can be controlled with high speed. To our knowledge, the present paper is the first report to clearly demonstrate surface form measurement with a spot size of approximately 1 mm for a low-reflective surface by deflectometry using a commercially available autocollimator. The proposed method can be used to measure a surface profile with arbitrary reflectivity by adjusting the power of the laser light source.

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