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STANDARDLESS PROFILE MEASUREMENT ALONG CIRCLES

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Abstract: In this paper, profiles along concentric circles on two precise mirrors are measured by using a Fizeau-interferometer with no standard. For the measurements, spacing between the two flat mirrors is measured with the interferometer at the angles of every 5 degrees along the circles. With these data, profiles are calculated using the Fourier transformation method and linear equation method. Profiles along ten concentric circles are calculated from the data although the mean plane of each profile is different. Discussion is made on the calculation of two-dimensional surface profiles along the different concentric mean planes. The results of the profiles calculated using different number of the data are compared with each other to show their respective features.
Keywords: Surface profile, Profile measurement, Precise mirror, Interferometer

1 INTRODUCTION

The profile measurements with no standard are especially important when the surface to be measured is precise, because it is difficult to obtain a standard for the precise surfaces.

Profiles along a circle on flat surfaces can be measured from spacing between two unknown surfaces along the circle. For the measurements, two unknown surfaces are placed almost in parallel and the spacing between them are measured along the circle. One of the surfaces is rotated around the center of the circle and the spacing are measured again. This measuring procedure is repeated many times. From these many spacing data, the two profiles are obtained by using the algorithms called the Fourier method or the simultaneous linear equation method. This measuring principle is verified in our previous papers using Fourier method [1].

In this study, we will measure spacing between two precise mirrors using a Fizeau-interferometer. The two profiles are calculated from the data using the above methods. On the basis of the calculated profile, the feature of the profile measurement is discussed.

2 MEASURING PROCEDURE [1][2]

Two unknown profiles of two surfaces along each circle with the same radius are shown schematically in Fig. 1. The two surfaces are set face to face almost in parallel. One of the surfaces named A is fixed and the other named B is rotatable around an axis normal to A. The 3-dimensional coordinates axes x, y and z are set on A with the rotational axis as the z axis. The measuring points are located on the circle with an equal angular interval.

The distances of space *W* between two surfaces are measured along the circle. The measurements are made again after B is rotated by the same angular interval as the measuring interval. This measuring procedure is repeated many times.

The distances consist of such unknown factors as profiles of two surfaces, inclinations and parallel displacement of the movable surface caused by the rotations. These unknown factors are linearly related to the measured distances.

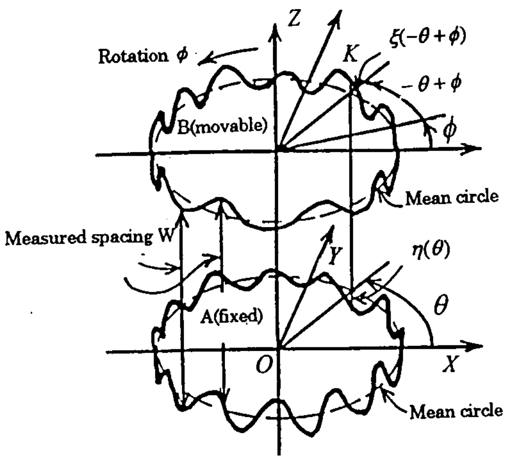


Figure 1. Schematic surfaces A and B

3 FORMULATION OF THE METHOD

3.1 Measuring equations

Figure 2 shows the coordinates and the geometrical relations in some details. Figure.2(b) shows a sectional view of A and B with I-I' section of a plan view shown in Fig. 2(a). The measured distance *W* is determined not only by profiles of two surfaces but also by inclinations and parallel displacement of B caused by the rotations. We represent the profiles of A as,profiles of B as,an inclination along x axis as, an inclination along y axis asand a parallel displacement as. The angular position of the measuring points is represented by,an angle of rotation of B byand a radius of the measuring circle by r. The symbols,,,andare unknown factors. A relation between the unknown factors and the measured distances are given in an equation (1).

When B is rotated by an amount, the position of A corresponds to the position -+ of B, because B is placed upside down. We shall call eq.(1) as a measuring equation. We can obtain the same number of equations as the number of the measuring points with differentand.

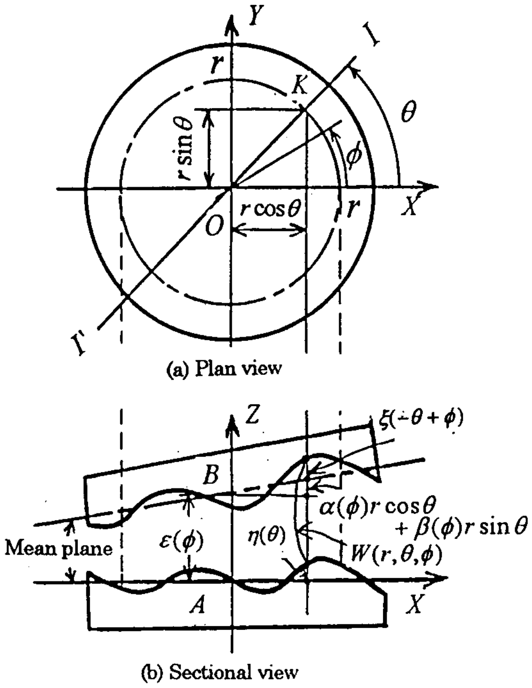


Figure 2. Inclinated of surfaces A and B

$$W(r,q,f) = -x(-q+f) - h(q) + a(f)r\cos q + b(f)r\sin q + e \tag{1}$$

3.2 Condition equations

Each profile is defined as a deviation from the mean plane in the least mean square sense. We can obtain the conditions of the profilesand in the following forms.

$$\int_0^{2p} x\cos q\,dq = 0, \int_0^{2p} x\sin q\,dq = 0, \int_0^{2p} x\,dq = 0 \tag{2}$$

$$\int_0^{2p} h\cos q\,dq = 0, \int_0^{2p} h\sin q\,dq = 0, \int_0^{2p} h\,dq = 0 \tag{3}$$

In this paper we shall call these equations as condition equations.

4 CALCULATION OF PROFILES

In the real situation we can obtain the measuring data at discrete sampling positions of q and j .

The measurements are made at the sampling positionsas the equation (4),

$$q_n = 2pn/N \ ; \ n = 0,1,2,\ldots,N-1 \tag{4}$$

and the angle of rotation is discrete as

$$f_m = 2pm/N \ , \ m = 0,1,2,\cdots,M-1 \tag{5}$$

where N is the number of division of the circle and M, which is equal to or smaller than N, is the number of the rotation.

We can rewrite the measuring equation (1) in the following discrete form,

$$W_{n.m} = -x_{-n+m} - h_n + a_m r\cos q_n + b_m r\sin q_n + e_m \tag{6}$$

and we can also rewrite the condition equations as follows,

$$\sum_{n=0}^{N-1} x_n \cos q_n = \sum_{n=0}^{N-1} x_n \sin q_n = \sum_{n=0}^{N-1} x_n = 0$$
$$\sum_{n=0}^{N-1} h_n \cos q_n = \sum_{n=0}^{N-1} h_n \sin q_n = \sum_{n=0}^{N-1} h_n = 0 \tag{7}$$

We can uniquely find the profiles using these measuring equations and condition equations with no standard.

We have two methods for calculating the profiles and from the measuring data of spacing W. One is a simultaneous linear equation method including the measuring equations and the condition equations. In this method, the number of rotations should be so chosen that that of equations exceed the number of unknown parameters. The other is a Fourier transformation method for the measuring data. In this method the number of rotations should be the same as the number of sampling points on one circle. We call the former method as the 1st method and the latter method as the 2nd method.

5 EXPERIMENTS

5.1 Measuring apparatus [2]

Figure 3 shows a Fizeau-interferometer as a measuring apparatus. Laser light is divided into two beams at the lower surface of the upper plate B; one is reflected at the surface and the other passes through it. The beam passing through the upper plate is reflected at the upper surface of the lower plate A. The two reflected lights interfere with each other and form the interference fringes as shown in Fig. 4. The fringe pattern corresponding to the spatial distance between the two reflecting surfaces. The fringes are slightly deviated from straight lines according to the deviation of the profiles from the flatness. In this experiment, one fringe corresponds to the distance of a half wavelength of the laser beam. The length of the wave is 633 nm. This equals to the shift of phase 2rad.

The lower plate A fixed on a rotary table can be rotated and its profile corresponds to $h(q)$ and that of the upper plate B corresponds to $x(q)$ in Eq. (1). Displacement and inclinations and vary at random by each rotation. In the present measurement, after acquiring one fringe pattern the lower plate is rotated by 5 degrees after acquiring one fringe pattern. The fringe pattern acquisitions are repeated many times.

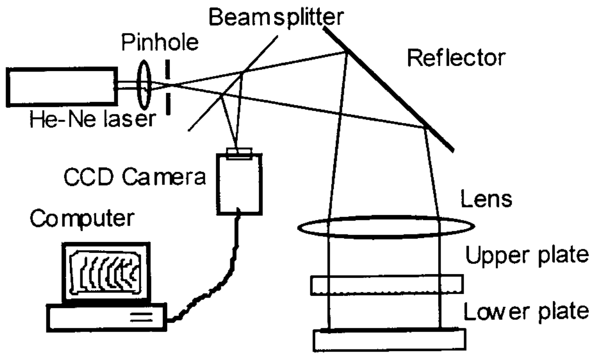


Figure 3. Fizeau-interferometer

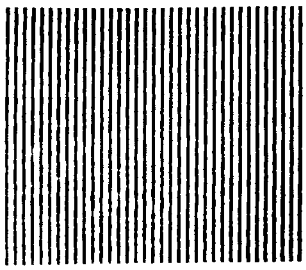


Figure 4. A fringe pattern

5.2 Spacing measurement

The distances of space W between the two surfaces are calculated by the Fourier transform method [3] for determining sub-fringe optical path length. In carrying out measurements, the fringe pattern is adjusted to the narrow fringes as shown in Fig. 4 so that the first order spectrum of the fringe pattern can be separated easily from the 0th order spectrum when the fringe intensity is transformed into Fourier spectrum.

The two surfaces to be tested are precise mirrors. The measuring points of the specimens are on ten concentric circles with a step of 5 degrees. The each radius of the circles is 7, 8, 9, 10, 11, 12, 13, 14, 15 and 16 mm respectively. The number of the measuring points on each circle is 72.

72 fringe patterns are obtained by the 72 rotations of the lower plate with a step of 5 degrees as a measuring interval. Figure 5 shows some examples of measured spacing along a circle with a radius 10 mm. Curves for different rotation angle have different shape. This fact means that the neither of the two surfaces is plane absolutely.

In the experiment, the spacing are measured with resolving power of about 0.5nm because we can calculate the shift of phase to about 0.01 rad. The picture elements of the CCD camera are arranged in meshed form. The data of spacing along circles are obtained by linear interpolation with four meshed data near the measuring point. The size of a pixel of the CCD camera corresponds

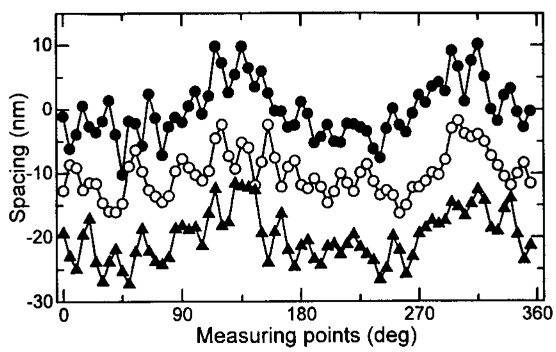


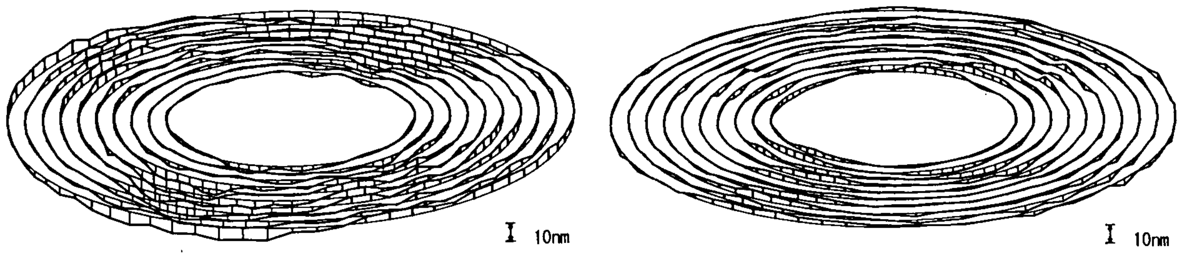
Figure 5. Spacing between two surfaces

to about 0.2 mm square on the measured surface.

6 RESULTS OF THE EXPERIMENTS

6.1 Profiles along ten circles

The profiles of the two surfaces are obtained using with the 1st method. They are calculated from the 6 sets of 72 spacing data. Figures 6 (a) and (b) show the obtained profiles along ten concentric circles on the upper plate and the lower plate. The short straight lines show the distances from the corresponding mean circles drawn in broken lines. Each profile has its own mean circle. The mean circles may have different inclination or different height. In this sense the profiles for the different radius is independent. In the figure, They are drawn as if they are on the same flat surface. From the figures we can take general views of 2-dimensional profiles of the two surfaces. The lower plate is finished less than 10 nm and the upper plate less than 15 nm in flatness. Both surfaces have wavy nature.



(a) The upper plate (b) The lower plate

Figure 6. Profiles along ten concentric circles

6.2 Calculation with the two methods

The two methods are the simultaneous linear equation method (the 1st method) and the Fourier transformation method (the 2nd method).

Figures 7 (a) and (b) show obtained profiles along a circle with radius 10mm on the upper plate and the lower plate respectively. In these figures, 3 profiles are calculated with the 1st method and 1 profile calculated with the 2nd method. For the 1st method, profiles are calculated with the data of 3, 4 and 6 rotations. The rotation angles are 0, 120 and 240 for 3 rotations, 0, 90, 180, and 270 for 4 rotations and 0, 60, 120, 180, 240 and 300 for 6 rotations. For the 2nd method, profiles are calculated with the data of 72 rotations. From the figure we can see that the measuring errors are smaller as the more data are used. However, for obtaining more data we have to perform many time-consuming experiments. Therefore, when the allowable error is not so small, the simultaneous equation method can be adopted for reducing the number of experiments. In the 2nd method, many experiments are necessary. However, the resultant profiles have small error and in addition the time of calculation for obtaining the profiles is very short compared with the simultaneous equation method.

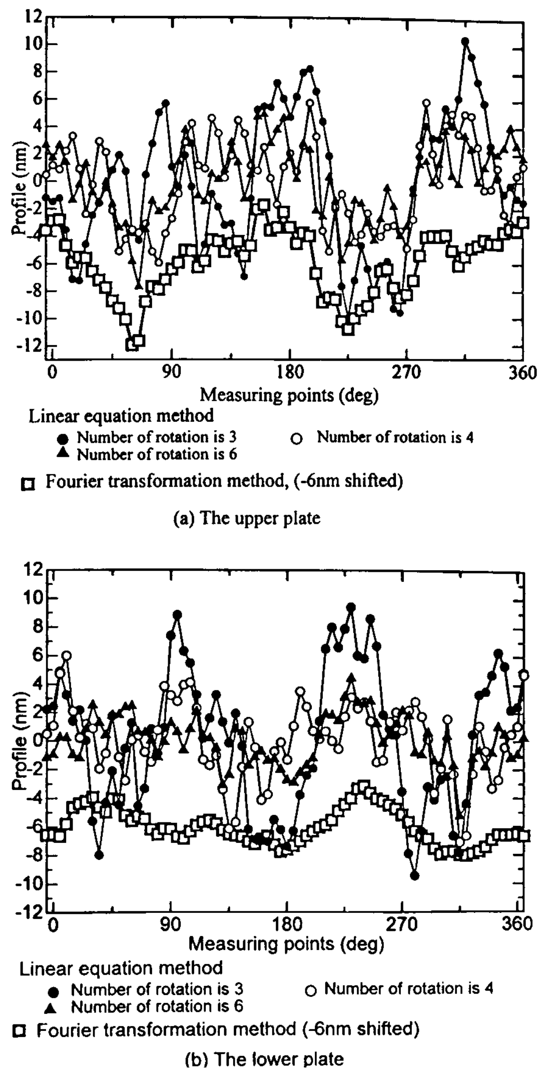


Figure 7. Comparison of profiles with two methods

7 CONSIDERATION

We can apply two calculation methods to obtain the profiles of surface along a circle with no standard. And we obtain profiles of two precise mirrors along ten concentric circles. But each obtained profile has each own mean circle. The position and the inclination of each mean circle is independent of each other. Therefore ten concentric circular profiles do not represent the 2 dimensional profile of surface strictly. In order to obtain 2 dimensional profiles using these circular profiles we must find the relation between them. For the purpose we may have to use a line standard. By using such standard, we can convert the independent circular profiles into the profiles based on the same plane.

8 CONCLUSION

The surfaces of two precise mirrors are tested with a Fizeau interferometer with no standard. One specimen is a precise mirror for the reference mirror in the interferometer. The other is a precise reflecting mirror. Ten profiles along ten coaxial circles on each surface are measured. These profiles can not be connected in the same plane, because the ten concentric mean circles are defined independently.

But these profiles can represent almost 2 dimensional profiles of the surfaces. The following conclusions are obtained.

(1) Profiles along ten circles on two precise mirrors are obtained.
(2) Both mirrors have wavy nature less than 15 nm.
(3) The Fourier transformation method has merits of short time for calculation and of a compensation effect for measuring errors.
(4) The simultaneous linear equation method has a merit of small number of measuring data for obtaining the profiles.

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