Invited Paper

Absolute measurement of optical surface profile with a Fizeau interferometer

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ABSTRACT

An optical surface profile is measured with a laser diode Fizeau interferometer using a method of absolute measurement. Wavefront aberration in the interferometer causes an undesirable phase distribution in the interference signal. To eliminate this phase distribution, the object surface is shifted in two directions orthogonal to each other and the difference wavefront of the surface profile of the object is obtained. An absolute surface profile is estimated by representing the object surface with a polynomial function and by solving the difference equations with least-squares method.

Keywords: absolute measurement, surface profile, difference wavefront, interferometer, sinusoidal phase modulation

1. INTRODUCTION

In profile measurement of a large optical flat surface wavefront aberrations existing in interferometers must be eliminated for achieving a high measurement accuracy of nanometer level. Although the three-flat method has been used for a long time, this method is not practical for easy and automatic measurements because two flats must be selected among three flats three times to be mounted in the interferometer as an object surface and a reference surface. The three-flat method was improved by adding the rotation of the object surface to make absolute measurement on the entire surface of the object[1, 2]. Moreover a parallel shift of the object surface was added to the three-flat method besides the rotation of the object surface, which is suitable to image detectors of a square grid structure[3]. In order to measure exactly the object surface without using the three-flat method many methods were proposed where rotations and parallel shifts are given to the object flat surface to be measured. These methods are called the two-flat method where a displaced object surface and a fixed reference surface are used. Exact measurement of a flat surface by shifting lineally the object surface in x and y directions orthogonal to each other was reported[4]. In this measurement the inclination of the object surface occurred during the parallel shift was tried to be eliminated from the measured wavefront by calculating the mathematical reference plan of the measured wavefront. However the inclination could not be completely eliminated because the mathematical reference plane of the shifted object surface is slightly different from that of the object surface before shifting it. Recently in order to estimate the inclination of the shifted object surface the following combinations of the shifts and rotation have been proposed: (1) a rotation on the original position of the object surface, a shift along x-axis, and a rotation on the shifted position[5], and (2) two shifts along x-axis and y-axis, and a rotation on the original position of the object surface[6]. In these two-flat methods difference wavefronts of

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the object surface are produced and processed to reconstruct the object surface profile or object wavefront in a similar way as in shearing interferometers. Methods for the reconstruction are mostly categorized as either zonal reconstruction or modal reconstruction. In zonal reconstruction the object wavefront is directly evaluated at specific grid points. Meanwhile in modal reconstruction, the object wavefront is expanded into a set of certain basis functions and its corresponding coefficients are evaluated.

In this paper the two-flat method with two shifts along x-axis and y-axis and the modal reconstruction with a polynomial function are used to measure exactly a flat glass surface. A reconstruction algorithm is proposed in which the coefficients of the polynomial function are estimated from one-dimensional difference data with least-squares method. A laser diode Fizeau interferometer insensitive to mechanical vibrations is used to detect the wavefronts with sinusoidal phase-modulating interferometry.

2. Sinusoidal Phase-Modulating Fizeau Interferometer[7-9]

Figure 1 shows a sinusoidal phase-modulating interferometer for measuring a surface profile of object. A laser diode (LD) is used as a light source of the interferometer in which a small change in the wavelength of the LD is generated by changing the injection current. When the wavelength of λ_0 changes by $\Delta\lambda$, the phase of the interference signal is given by

$$\alpha_L=2\pi L/(\lambda_0+\Delta\lambda)=2\pi L/\lambda_0 - 2\pi(\Delta\lambda/\lambda_0^2)L\,, \qquad (1)$$

where L is optical path difference, and $\Delta\lambda^2$ is neglected in the expansion of the equation. The first tem of phase α_L is denoted by $\alpha=2\pi L/\lambda_0$ that is produced with the wavelength of λ_0 When $\Delta\lambda= -b\cos(\omega_c t+\theta)$ is generated by changing the injection current, the following interference signal in the sinusoidal phase-modulating interferometer is obtained:

$$\begin{aligned} S_D(t) &= A+B\cos[Z\cos(\omega_c t+\theta)+\alpha] \\ &= A + B\cos\alpha\, [J_0(Z)-2J_2(Z)\cos(2\omega_c t+2\theta)+\ldots] \\ &\quad -B\sin\alpha\, [2J_1(Z)\cos(\omega_c t+\theta)-2J_3(Z_b)\cos(3\omega_c t+3\theta)+\ldots]\,, \end{aligned} \qquad (2)$$

where A is a constant, B is amplitude of the time-varying component, and $J_n(Z)$ is the n-th Bessel function. The modulation amplitude is $Z=2\pi bL/\lambda_0^2$, and β is the modulation efficiency of the LD. Denoting Fourier transform of $S_D(t)$ by $F(\omega)$, the modulation amplitude Z and the modulation phase θ are obtained from $F(\omega_c)$ and $F(3\omega_c)$. The phase α representing the surface profile is obtained from $F(\omega_c)$ and $F(2\omega_c)$ with known values of Z and θ. A two-dimensional CCD image sensor (hereafter it is called CCD) is required for measurement of the surface profile. The output of the CCD is an integration of the time-varying signal S(t) over the storage period of the CCD. Fourier transform $F(\omega)$ is obtained from the output of the CCD.

The fluctuation in phase of the interference signal caused by mechanical vibrations is expressed by $\eta(t)$. The constant component A in the interference signal detected with a photodiode is eliminated with an electric circuit of a high-pass filter. By sampling the signal of $B\cos[Z\cos(\omega_c t+\theta)+\alpha+\eta(t)]$ when $\cos(\omega_c t+\theta)$ is equal to zero, a phase signal

$$S_F(t)= B_F\cos[\alpha(t)+\eta(t)] \qquad (3)$$

is obtained on one point of the object surface. This signal is used as a feedback signal with which the injection current of the LD is controlled to keep the phase $\alpha(t)+\eta(t)$ at a constant value. When the injection current changes by i_C, the phase α of the interference signal changes by $\alpha_C=-2\pi(\beta i_C/\lambda_0^2)L$. The injection current is controlled so that $S_F(t)$ becomes to zero with proportional and integral feedback controller. Then the phase of $\alpha(t)+\eta(t)$ becomes to a constant of $\pi/2$ even if there are mechanical vibrations. Thus the effect of the mechanical vibrations is eliminated over the object surface.

If the mechanical vibration is instantaneous and strong, the elimination by the feedback control mentioned above is not enough. The fluctuation in the $S_F(t)$ is observed whether the magnitude A_F of the fluctuation exceeds a specified value H_F. When A_F is smaller than H_F, the interference signal is fed to a computer. If it is fed to a computer continuously for a specified period, the capture of the interference signal is completed. This operation is called the automatic capture without vibration.

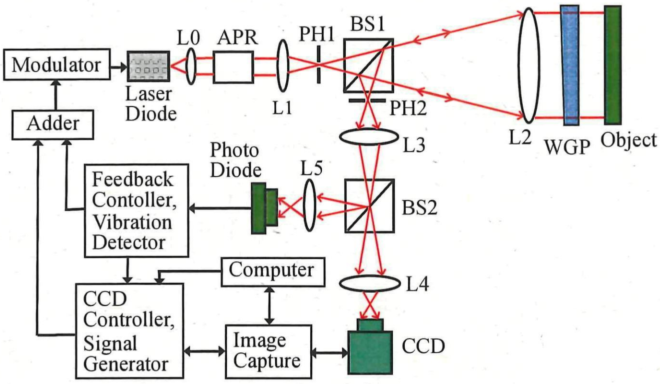

Fig.1 Sinusoidal phase-modulating Fizeau interferometer insensitive to mechanical vibrations.

3. Method of Absolute Measurement

The measured wavefront obtained from the phase $\alpha(x,y)$ of the interference signal is expressed by

$$D(x,y)=O(x,y)-R(x,y)\,, \qquad (4)$$

where $O(x,y)$ is produced by the surface profile of the object, and it is the object wavefront to be measured. Wavefront aberration $R(x,y)$ is produced mainly by the fact that the reference surface of the wedged glass plate (WGP) is not perfectly flat, and partially by the fact that the light incident to the object and WGP is not perfect plane wave. In order to eliminate the aberration $R(x,y)$ the object is shifted in the x-axis by Δ to measure a wavefront

$$D(x+\Delta,y)=O(x+\Delta,y)-R(x,y)\,. \qquad (5)$$

The difference wavefront is obtained from Eqs.(4) and (5) and it does not contain the wavefront aberration $R(x,y)$ as follows:

$$S(x,\Delta)= D(x+\Delta,y)- D(x,y)= O(x+\Delta,y)-O(x,y)\,. \qquad (6)$$

Here it is assumed that the object wavefront to be measured can be represented by

$$O(x,y)=ax^4+bx^3y+cx^2y^2+dxy^3+ey^4+fx^3+gx^2y+hxy^2+iy^3+jx^2+kxy+py^2+qx+ry+s\,. \qquad (7)$$

A polynomial function of two variables given by Eq.(7) is regarded as a function of one variable x under the condition that the variable y is constant as follows:

$$O(x)=ax^4+(by+f)x^3+(cy^2+gy+j)x^2+(dy^3+hy^2+ky+q)x+(ey^4+iy^3+ly^2+ry+s)$$
$$=a_4x^4+a_3x^3+a_2x^2+a_1x+a_0 \quad . \qquad (8)$$

Then the difference equation along the x-axis at one value of the y-coordinate is expressed as follows:

$$S(x,\Delta)=O(x+\Delta)-O(x)$$
$$=(4x^3\Delta+6x^2\Delta^2+4x\Delta^3+\Delta^4)a_4+(3x^2\Delta+3x\Delta^2+\Delta^3)a_3+(2x\Delta+\Delta^2)a_2+\Delta a_1 . \qquad (9)$$

The x-coordinates of the sampling points of the difference function $S(x,\Delta)$ are denoted by x_l , where l is an integer from -L to L. Also the y-coordinates of the sampling points are denoted by y_m , where m is an integer from -M to M. The coefficients a_4 to a_l in Eq.(9) can be estimated at one value of the y-coordinate by using the least squares method. The coefficients a_4 to a_l estimated at $y=y_m$ are denoted by a_{4m} to a_{lm}. Average value of a_{4m} (m=-M to M) is assigned to the value of a_4=a. Regarding the coefficient a_3=by+f, the values of b and f can be estimated with the least squares method using the following equation:

$$\begin{pmatrix} y_{-M} & 1 \\ \vdots & \vdots \\ y_m & 1 \\ \vdots & \vdots \\ y_M & 1 \end{pmatrix}\begin{pmatrix} b \\ f \end{pmatrix}=\begin{pmatrix} a_{3-M} \\ \vdots \\ a_{3m} \\ \vdots \\ a_{3M} \end{pmatrix} \quad . \qquad (10)$$

In a similar way, the coefficients c, g, and j are estimated from a_{2m} (m=-M to M), and the coefficients d, h, k, and q are estimated from a_{lm} (m=-M to M). Therefore the coefficients a, b, c, d, f, g, h, j, k, and q are estimated from the difference equation $S(x,\Delta)$ along the x-axis. Next the difference equation $S(y,\Delta)$ along the y-axis is also processed in the same way to estimate the coefficients b, c, d, e, g, h, i, k, p, and r. Since the coefficients b, c, d, g, h, and k are estimated from both $S(x,\Delta)$ and $S(y,\Delta)$, their average values are assigned to the finally estimated values. Therefore the absolute measurement of the surface profile can be achieved by obtaining the coefficients in Eq.(7) except the coefficients q, r, and s which represents the tilts and piston of the surface.

4. Fizeau Interferometer

Figure 1 shows a configuration of a laser diode Fizeau interferometer insensitive to vibrations for surface profile measurement. Wavelength of the laser diode is 685 nm and its maximum output power is 60 mW. Light from the LD is collimated with Lens L0. The elliptic pattern of the beam is converted to a circular pattern with an anamorphic prism pair APR. Objective lens L1 makes the beam diverge to be 100 mm-diameter in the front of lens L2 whose focal distance is 500mm. The diameter of pinhole PH1 is 50 μm. The collimated beam is incident to WGP of 1 degree and the object. Object light reflected by the surface of the glass plate and the reference light reflected by one side of WGP are turned by 90 degrees by beam splitter BS1. The light reflected by another side of WGP is blocked by pin hole PH2 of 100 μm-diameter. An image of the object is made on CCD by lens L2, L3, and L4 with a magnification of 1/45. An image of the object on the photo diode is also made by lens L2, L3, and L5. Beam splitter BS2 is a polarizing one, and its reflectivity is about 90 % for the polarization angle of the light adjusted by rotating LD and APR. The sinusoidal phase-modulating interference signal produced by modulating the injection current of the LD with a frequency of 375 Hz is detected with the CCD to obtain the phase $\alpha(x,y)$ of the interference signal.

Figure 3 shows the feedback signal $S_F(t)$ when the feedback control works well, and the amplitude A_F of $S_F(t)$ is smaller than H_F. When instantaneous vibration occurs in the inteferometer, the amplitude A_F exceeds to the amplitude of H_F as shown in Fig.3 because the feedback control does not completely reduce the effect of the instantaneous vibration. The interference signal is captured when the amplitude A_F is less than H_F. A capturing time T_P of 0.53 s is needed for the required interference signal to be detected with the CCD. In Fig.3 the signal capture starts, but it stops before the capturing time becomes T_P because the amplitude A_F exceeded H_F due to the instantaneous vibration. The signal capture automatically restarts when the amplitude A_F falls to H_F. After that the amplitude A_F is less than H_F during the capturing time T_P, and the signal capture finishes. The interference signal is automatically detected during the vibration-free period.

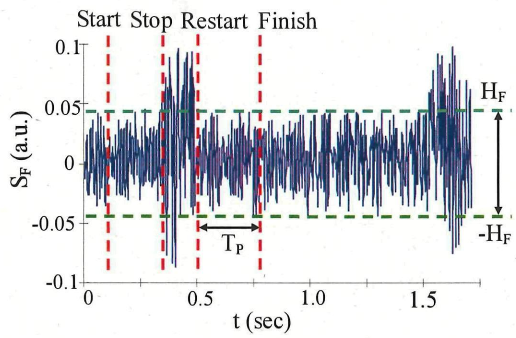

Fig.3 Capture of interference signal by detection of vibration-free period.

5. Measurement results

The object was a surface profile of a glass plate of 80 mm-diameter with $\lambda/20$ PV. The measured wavefront $D(x,y)$ was obtained by subtracting a mathematical reference plane which represented the tilt and piston components contained in the detected phase distribution $\alpha(x,y)$. The wavefront $D(x,y)$ is shown in Fig.4, where the coordinate of the measurement point is given by (0.45x mm, 0.45y mm) and the number of the measurement points is 121×121. The wavefront $D(x,y)$ is regarded as a surface profile by representing the vertical axis in nanometers. The object was shifted along the x direction by Δ=4 mm, and the wavefront $D(x+\Delta,y)$ was obtained after subtracting the tilt and piston components from its raw distribution. Figure 5 shows the difference wavefront $S(x,\Delta)= D(x+\Delta,y)- D(x,y)$. It is assumed that the mathematical reference planes corresponding to $O(x+\Delta,y)$ and $O(x,y+\Delta)$ are almost the same as that corresponding to $O(x,y)$. The difference wavefront $S(y,\Delta)$ of Δ = 4 mm was also obtained. The object wavefront $O(x,y)$ without the tilt and piston components was reconstructed by the method of the absolute measurement described in Sec.3, as shown in Fig.5. The PV value and RMS value of $O(x,y)$ were 8.9 nm and 1.5 nm, respectively. By subtracting $O(x,y)$ from $D(x,y)$ the wavefront aberration $R(x,y)$ was obtained as shown in Fig.6. The PV value and RMS value of $R(x,y)$ were 46 nm and 4.3 nm, respectively.

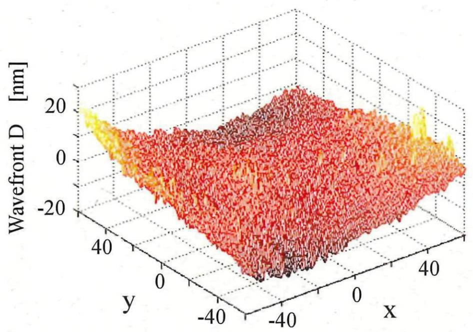

Fig.4 Measured wavefront D(x,y).

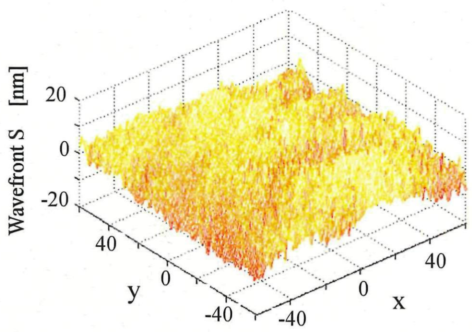

Fig.5 Difference wavefront S(x, Δ).

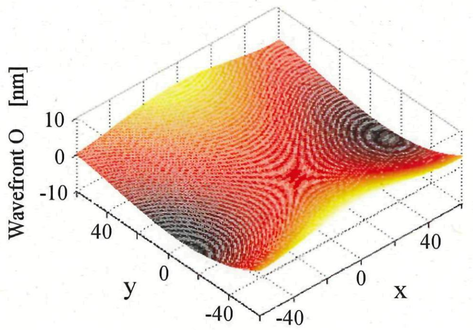

Fig.6 Reconstructed object wavefront O(x, y).

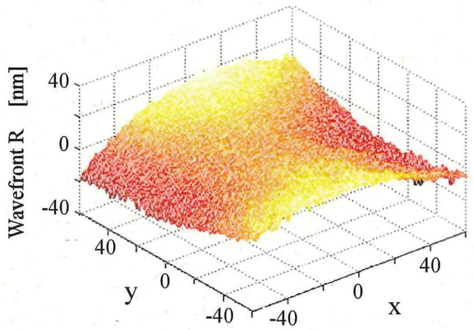

Fig.7 Estimated wavefront aberration R(x, y).

5. CONCLUSION

A surface profile of the optical flat glass plate was measured in the measuring region of about 45mm square with a laser diode Fizeau interferometer insensitive to mechanical vibrations. The difference wavefronts with the shift amount of 4 mm in the x and y direction were obtained through subtracting the tilt and piston components from the measured wavefronts. The inclination of the object surface occurred during the shift could not completely eliminated by this subtraction. The object wavefront was reconstructed by estimating coefficients of the two-dimensional polynomial function for expressing the object surface. This estimation was carried out with the least squares method by regarding the two-dimensional polynomial function as one-variable function. The PV value and RMS value of the reconstructed object wavefront were 8.9 nm and 1.5 nm, respectively, and their values were very smaller than those of the estimated wave aberration.

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