Measurement of cylinder diameter by using sinusoidally vibrating sinusoidal gratings

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ABSTRACT

We propose a new method for measuring a position of an endpoint of a metal cylinder in which a sinusoidal intensity distribution vibrating sinusoidally is used. The position of the endpoint is measured as a phase of a sinusoidally phase-modulated signal which is generated from a light diffracted from the endpoint. In order to extend the measurement range and measure a diameter of a metal cylinder two sinusoidal intensity distributions with two different periods of P_1=100 μm and P_2=98 μm are used. Cylinder diameters are exactly determined from the measurements for two endpoints of a cylinder using the two periods. Experimental results make it clear that the measurement error is less than 0.3 μm for a cylinder metal of 3885.2 μm diameter.

1. INTRODUCTION

For measuring an outer diameter of an object a collimated laser beam is illuminated to the object and the intensity distribution just behind the object is measured. A laser beam of a very small diameter is scanned across the object surface and the time interval during which the laser beam is blocked by the object is measured. In these methods measurement error is a few macrons because there is diffraction of the beams by the endpoints of the object. In this paper, by using a collimated laser beam with sinusoidal intensity distribution the information on a position of the endpoint is added to the light diffracted by the endpoint. The information on the position is converted into a phase of a time-varying sinusoidal signal by sinusoidally vibrating the sinusoidal intensity distribution of a period P_S. In this conversion the position can be measured with a resolution of about $P_S/300$ in the measurement range less than P_S. In order to extend the measurement range two sinusoidal intensity distributions with two different periods are used. In experiments 3.9mm-diameter of a metal cylinder is measured with a measurement error less than 0.3 μm by using the two periods of P_1=100 μm and P_2=98 μm.

2. PRINCIPLE OF POSITION MEASUREMENT

Figure 1 shows a configuration of the setup for measuring a position x_0 of an endpoint of a cylinder. The collimated light from the laser diode (LD) is illuminated onto a grating G of sinusoidal intensity pattern of a period P_S. The grating is vibrating sinusoidally with a waveform of $Z\sin(\omega_c t+\theta)$. A Fourier image of the grating exists on the x-axis, and the time-varying component of light intensity on the position x_0 is given by

$$S_D(t)=\cos[Z\sin(\omega_c t+\theta)+\alpha] \qquad \alpha=2\pi x_o/P_S . \qquad (1)$$

Light diffracted by the endpoint of the cylinder is gathered with Lens L2, and detected with a photodiode (PD). The time-varying component of the output signal from the PD is also given by Eq.(1). The signal $S_D(t)$ is a sinusoidally phase-modulated signal, and it is Fourier-transformed to calculate the values of Z, θ, and α. [1] The calculated value of α gives us the position x_0 of the endpoint of a cylinder.

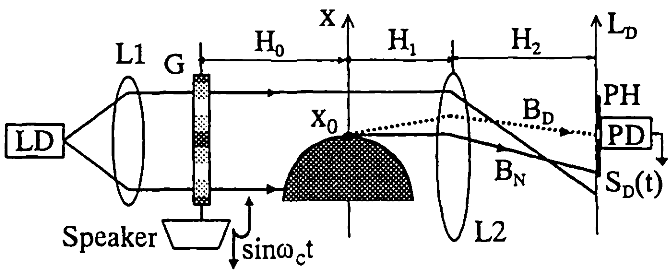

Fig.1 Configuration of the setup for measuring a position x_0 of an endpoint of a cylinder.

3. SETUP AND POSITION MEASUREMENT

Figure 2 shows a configuration of the setup for measuring a diameter of a metal cylinder. The cylinder is put into light beams, and positions x_{01} and x_{02} of the upper and lower endpoints are measured. The collimated light from LD1 and the grating G1 of 100 μm period produce a sinusoidal intensity distribution with a period of 100 μm on the x-axis. The collimated light from LD2, the grating G2 of 100 μm period, lens L4, and lens L5 produce the sinusoidal intensity distribution with a period of 98 μm on the x-axis. The position of L5 is adjusted to obtain the period of 98 μm. Using the two sinusoidal intensity distributions with two different periods of P_1=100 μm and P_2=98 μm leads to a wide measurement range which is specified by a synthetic period of $P=P_1P_2/P_1-P_2$ =4900 μm. Measurement of a diameter of a metal cylinder with the two periods will be described in Sec.4.

In this section we use only a sinusoidal intensity distribution of P_1=100 μm in order to show how to obtain the signal $S_D(t)$ for the two endpoints of a metal cylinder with a diameter of about 4 mm. In Fig.1 we consider a beam B_D of the diffracted light shown by the dotted line and a beam B_N whose propagation direction does not change at the endpoint. When the distance H_1 between the endpoint and the lens L2 is equal to the focus length f_2 of the lens L2, all beams of light diffracted from the endpoint x_0 propagate in the same direction. When H_1 is a little less than f_2, the beam B_D separates more greatly from the beam B_N as the distance H_2 between the lens L2 and the detection plane is longer. In experiments light diffracted at the endpoints was observed being distinguished from the transmitted light for a metal cylinder of about 3.9 mm diameter when H_1 was about f_2=16 mm and H_2 was 80 mm. We detected intensity distribution I along an axis

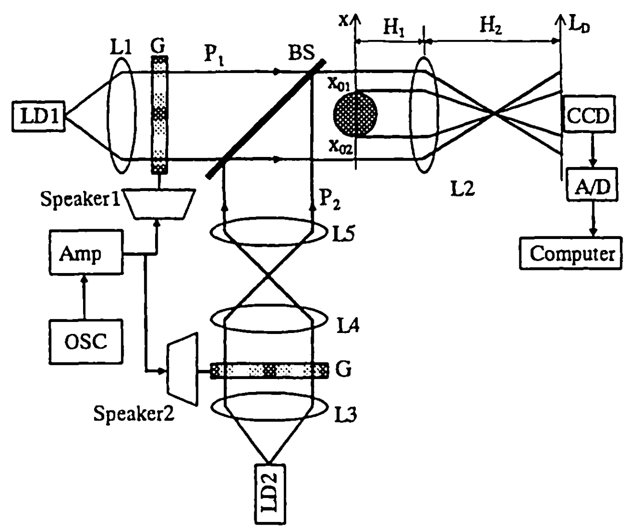

Fig.2 Configuration of the setup for measuring a diameter of a metal cylinder.

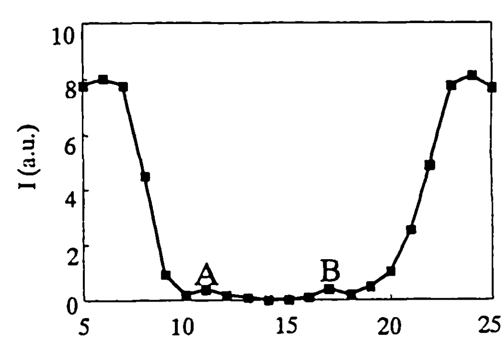

Fig.3 Detected intensity distribution.

L_D at the detection plane with a PD in the setup of Fig.2. Detected intensity distribution is shown in Fig.3, where there are two small peaks at the positions indicated by A and B. These peaks are generated by the light diffracted at the endpoints. We detected the signal $S_D(t)$ around the positions of A and B with a linear CCD image sensor at $\omega_c/2\pi=60$ Hz, and calculated phase α with the signal processing described in Ref.2. The results are shown in Figs.4 and 5, where the horizontal axis is the cell number of the CCD whose interval is 14μm. From these results it is concluded that the position of the endpoint can be measured from a constant value of the phase α containing in the diffracted light which generates a small peak in the intensity distribution. The measurement error ε_α is less than about 0.02 rad.

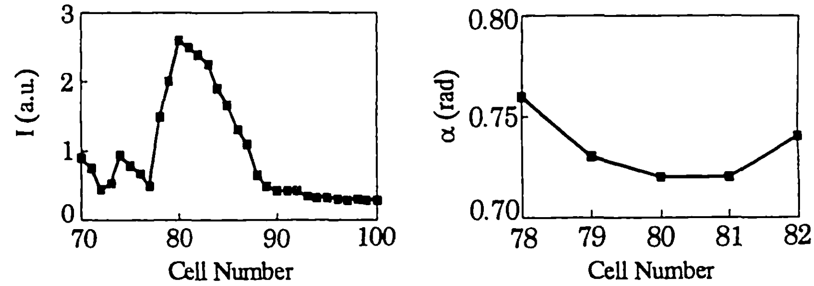

Fig.4 Detected intensity and phase distributions around A.

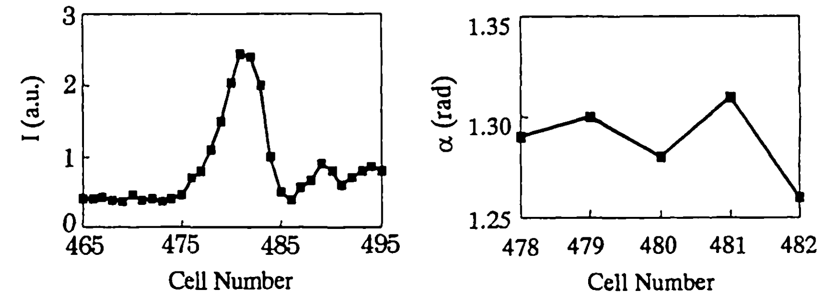

Fig.5 Detected intensity and phase distributions around B.

4. DIAMETER MEASUREMENT

Figure 6. shows the scales which are used for the measurement of cylinder diameter D. Two phases α_{1L} and α_{1R} for the positions x_{oL} and x_{oR} of the endpoints are measured with the sinusoidal intensity distribution of P_1=100 μm. Similarly two phases α_{2L} and α_{2R} for the endpoint positions are measured with the sinusoidal intensity distribution of P_2=98 μm. The positions are expressed in the x-coordinate whose origin is assumed to be coincident with zero phase of the period of P_1=100 μm and phase α_{2S} of the period of P_2=98 μm, as shown in Fig.6. In these situations the position x_{oL} is expressed by

$$x_{oL}= l_1P_1+(\alpha_{1L}/2\pi)\, P_1 = l_2P_2+(\alpha_{2L}/2\pi)\, P_2 - (\alpha_{2S}/2\pi)\, P_2, \qquad (2)$$

where l_1 and l_2 are positive integers. Putting $P=P_1P_2/(P_1-P_2)$ and $\alpha_L=\alpha_{2L}-\alpha_{1L}$ in the expression $(x_{oL}/P_2)-(x_{oL}/P_1)$ obtained from Eq.(2), we have

$$x_{oL} = P(l_2-l_1) + P(\alpha_L/2\pi) - P(\alpha_{2S}/2\pi)\,. \qquad (3)$$

The position x_{oR} is also expressed with the same relations and $\alpha_R=\alpha_{2R}-\alpha_{1R}$, and we have

$$D = x_{oR} - x_{oL} = P(\alpha_D/2\pi)\,, \qquad (4)$$

where α_D is determined by choosing one from relations of $\alpha_D=\pm(\alpha_R-\alpha_L)$ and $\alpha_D=2\pi\pm(\alpha_R-\alpha_L)$ so that α_D corresponds to the real value of D. Measured value obtained from Eq.(4) is denoted

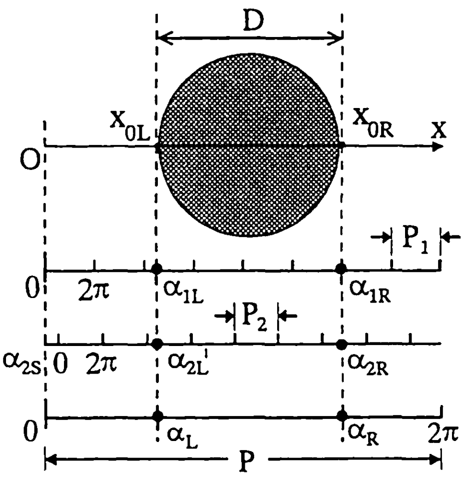

Fig.6 Scales used for measurement of cylinder diameter D.

by D_S. Diameter is expressed by

$$D=m_1P_1+D_1= m_2P_2+D_2\,, \qquad (5)$$

where m_1 and m_2 are positive integers. A fine value D_1 of the diameter D is given by

$$D_1= P_1(\alpha_{D1}/2\pi) < P_1\,, \qquad (6)$$

where α_{D1} is determined by choosing one from relations of $\alpha_{D1}=\pm(\alpha_{1R}-\alpha_{1L})$ and $\alpha_{D1}=2\pi\pm(\alpha_{1R}-\alpha_{1L})$ so that α_{D1} corresponds to the value of D_S. A fine value D_2 of the diameter is also obtained with the same relations. From measured values D_S and D_1 we calculate

$$m_{C1}=(D_S- D_1)/P_1\,. \qquad (7)$$

If the measurement error ε_{DS} in D_S is smaller than $P_1/2$, we can determine the integer m_1 by rounding off the value of m_{C1} to an integer. Since the measurement error ε_α in α_D is less than 2×0.02 rad, the measurement error ε_{DS} in D_S is less than 31 μm. In this measurement error the diameter can be obtained from Eq.(5) with the measurement error less than 0.3 μm.

Measurement results are shown in Table 1. We gave a displacement to the cylinder along the x axis at intervals of 10 μm. Six measurements were made at the different positions of Δx. Differences between the value of m_{C1} and an integer of its round number are within 0.2. An average value of the cylindrical diameter is 3885.2 μm and its measurement error in D_1 is about 0.3 μm.

Table 1 Measurement Results.

Δx	α_{1L}	α_{1R}	α_{2L}	α_{2R}	α_L	α_R	α_D	D_S	D_1	m_{C1}	D
0	1.39	2.30	1.56	−2.52	0.17	−4.28	4.99	3891.5	85.5	38.1	3885.5
10	0.73	1.67	0.88	−3.13	0.15	−4.80	4.95	3860.3	85.0	37.8	3885.0
20	0.10	1.03	0.26	2.51	0.16	1.48	4. 96	3868.1	85.1	37.8	3885.1
30	−0.49	0.43	−0.33	1.87	0.16	1.44	5. 00	3899.3	85.3	38.1	3885.3

α_{1L}(rad), α_{1R}(rad), α_{2L}(rad), α_{2R}(rad), α_L(rad), α_R(rad), α_D(rad), Δx(μm), D_S(μm), D_1(μm), D(μm)

5. CONCLUSION

We constructed the setup for measuring a position of the endpoint of the metal cylinder in which the sinusoidally vibrating sinusoidal grating was used and the light diffracted from the endpoint was extracted. The position of the endpoint was measured as a phase of the sinusoidally phase-modulated signal. In order to measure a diameter of the metal cylinder the two sinusoidal intensity distributions with the two different periods of P_1=100 μm and P_2=98 μm were used. Experimental results made it clear that the measurement error in the diameter is less than 0.3 μm.

REFERENCES

1. O.Sasaki and H.Okazaki, "Sinusoidal phase modulating interferometry for surface profile measurement," Appl. Opt. 25, 3137-3140 (1986).
2. O.Sasaki and H.Okazaki, "Detection of time-varying intensity distribution with CCD image sensors," Appl. Opt. 24, 2124-2126 (1985).