Real-time measurement of one-dimensional step profile with a sinusoidal wavelength-scanning interferometer using double feedback control

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Abstract. A linear CCD image sensor is used to electrically scan a measuring point and measure 1-D step-profiles in real time with a sinusoidal wavelength-scanning (SWS) interferometer using double feedback control. In this interferometer, the optical path difference (OPD) and the amplitude of the SWS are controlled so that a ruler marking every wavelength and a ruler with scales smaller than a wavelength are generated. These two rulers enable us to measure an OPD longer than a wavelength in real time. Two different step profiles with step heights of 1 and 20 μm, respectively, are measured with a measurement error of less than 8 nm. Measuring time for one measuring point is 0.04 s. [DOI: 10.1117/1.1737375]

Subject terms: step-profile measurement; interferometer; wavelength scanning; phase lock.

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1 Introduction

Real-time measurement of a 1-D surface profile with an accuracy of a few nanometers is required to inspect surface profiles of manufacturing products in a short time. To satisfy this requirement we developed a phase-locked laser diode interferometer using sinusoidal phase modulation.[1] A linear CCD image sensor was used to scan electrically a measuring point along a line on an object's surface. A phase of the interference signal was locked at a fixed value by feedback, controlling the injection current of the laser diode (LD) during the scanning of the measuring points. Since sinusoidal phase modulation produces an interference signal that is continuous with time and contains fundamental and harmonic components of a sinusoidal phase-modulation signal, it is very easy to generate accurate feedback signals for the phase lock with electrical circuits in real time even when the CCD image sensor is used. However this phase-locked interferometer could not measure a step profile with a step height greater than half a wavelength because it was difficult to determine whether or not the phase change was larger than 2π. To measure an optical path difference (OPD) longer than a wavelength in real time, a phase change caused by wavelength scanning was detected with a heterodyne interferometer[2] or a phase-shift-locked interferometer[3] for distance measurement. In the case where wavelength scanning is incorporated into interferometers, sinusoidal wavelength scanning (SWS) is also very suitable for 1-D measurement in real time. We proposed an SWS interferometer using double feedback control as a new phase-locked interferometer.[4] In this interferometer, the conventional phase was locked at a fixed value by controlling the OPD while the phase-modulation amplitude generated by the SWS was also locked at a fixed value.

In this paper, we apply the SWS interferometer using double feedback control to measure 1-D step profiles whose step heights are more than a wavelength. A linear CCD image sensor is used to scan the measuring points electrically and the interference signal is processed with electric circuits to carry out the feedback controls, so that step profiles are measured in real time. The principle of the SWS interferometer using double feedback control is reviewed first. Detection of the interference signal with the CCD image sensor is explained, and characteristics of the feedback controls involving the CCD image sensor are analyzed. In experiments, a ruler marking every wavelength is obtained, and 1-D step-profile measurements are performed for two different step heights of 1 and 20 μm.

2 Principle

Figure 1 shows the setup of the interferometer. A continuous spectrum of the superluminescent diode (SLD) appears on the focal plane of lenses L_2 and L_3. Slit SL transmits a portion of the spectrum. The first-order reflection from the grating G_2 produces a collimated beam whose propagating direction is constant for all of the wavelengths contained in the spectrum of the SLD. The slit is connected with a magnetic coil of a speaker and vibrated sinusoidally with an angular frequency of ω_b. The central wavelength of the light passing through the slit is sinusoidally scanned and it

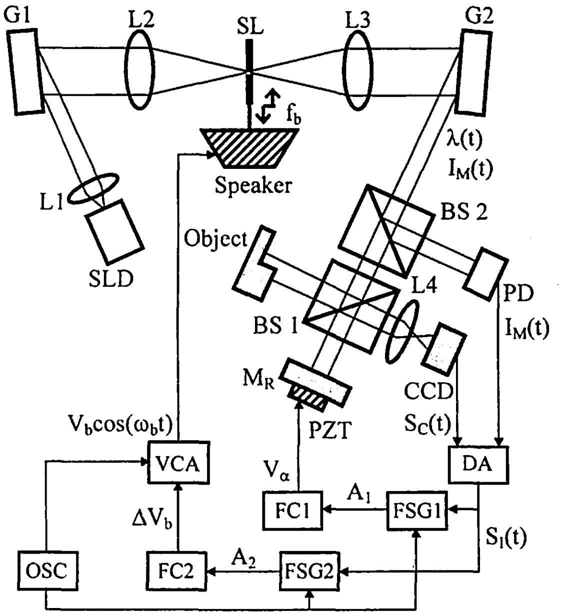

Fig. 1 SWS interferometer for real-time step-profile measurement.

is expressed by $\lambda(t)=\lambda_0+b\cos(\omega_b t)$. Intensity $I_M(t)$ of the beam is detected with a photodiode (PD). Although a CCD image sensor detects an interference signal in Fig. 1, it is assumed in this principle that a photodiode detects an interference signal which is denoted by $S_D(t)$. Detection with a CCD image sensor whose output is denoted by $S_C(t)$ is described in Sec. 3. Here $S_D(t)$ is divided by the intensity $I_M(t)$ to obtain a normalized interference signal as follows:

$$\begin{aligned} S(t) &= S_D(t)/I_M(t) \\ &= A+B\cos(Z_b\cos\omega_b t+\alpha) \\ &= A+B\cos\alpha[J_0(Z_b)-2J_2(Z_b)\cos(2\omega_b t)+\cdots \\ &\quad -B\sin\alpha[2J_1(Z_b)\cos(\omega_b t)-2J_3(Z_b)\cos(3\omega_b t) \\ &\quad +\cdots], \end{aligned} \tag{1}$$

where A and B are constants, and

$$Z_b=(2\pi b/\lambda_0^2)L, \tag{2}$$

$$\alpha=-(2\pi/\lambda_0)L. \tag{3}$$

Also L is an OPD, and J_n is the nth order Bessel function.

First, we explain how to measure a fractional value of OPD L with a feedback control. Feedback signal generator FSG1 generates a feedback signal $A_1=BJ_2(Z_b)\cos\alpha=g\cos\alpha$. Feedback controller FC1 produces voltage V_α applied to the piezoelectric transducer (PZT). The feedback system controls the position of reference mirror M_R or OPD so that the feedback signal A_1 becomes zero. The change of the OPD caused by this feedback control is illustrated in Fig. 2. At first the OPD is L and the position of signal A_1 is point Q. The position of signal A_1 moves to stable point P by the feedback control. Then phase α becomes $3\pi/2+2m\pi$, where m is an integer. The OPD at the stable point of the feedback control is given by

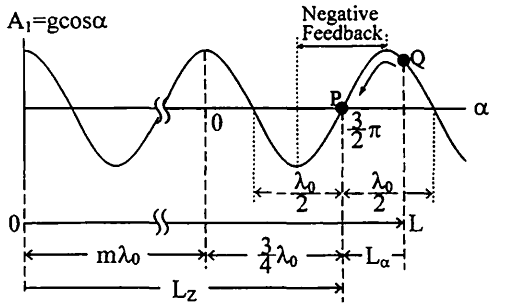

Fig. 2 Change in the OPD by feedback, which keeps phase α at $3\pi/2$.

$$L_z=L-L_\alpha=3\lambda_0/4+m\lambda_0, \tag{4}$$

where L_α is a fractional value of OPD L, which can be measured by detecting the applied voltage V_α and using the relation of $L_\alpha=\beta V_\alpha$. Its measurement accuracy is of the order of nanometers.

Next, we explain how to measure an integer multiple of the wavelength in the OPD L. A feedback signal of $A_2=2B\sin Z_b$ is generated with feedback signal generator FSG2 in the condition of $\alpha=3\pi/2+2m\pi$. Feedback controller FC2 produces voltage ΔV_b, which is fed to voltage control amplifier (VCA) and determines the amplitude V_b of the voltage applied to the speaker. The feedback system controls the amplitude V_b or the amplitude b of the wavelength scanning so that the signal A_2 becomes zero. This makes modulation amplitude $Z_b=(2\pi b/\lambda_0^2)L_z$ equal to π. Then the following equation holds:

$$b=\lambda_0^2/2L_z=2\lambda_0/(4m+3). \tag{5}$$

Values of b are discrete, corresponding to values of m. Since the amplitude b is proportional to the amplitude V_b, values of V_b are also discrete. These discrete values of the amplitude V_b at which Z_b is equal to π are refereed to as stable points of V_b.

A value of b is found, knowing the measured value of V_b, and a measured value of L_Z is calculated by the relation of $L_Z=\lambda_0^2/2b$. Since L_Z is given by Eq. (4), the following value is calculated using the measured value of L_Z:

$$m_c=(L_z-3\lambda_0/4)/\lambda_0. \tag{6}$$

Integer m can be determined by rounding off the value of m_c to an integer if measurement error of L_z is smaller than $\lambda_0/2$. Finally the OPD is calculated with a formula

$$L=3\lambda_0/4+m\lambda_0+L_\alpha. \tag{7}$$

It is noted that once the relation between the integer values of m and the stable points of V_b is given, the OPD can be obtained directly from Eq. (7) without calculation of m_c. This means that the stable points of V_b is regarded as

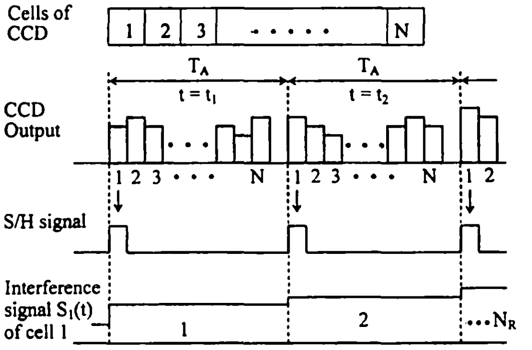

Fig. 3 Generation of interference signal for a specified cell of the CCD image sensor.

a ruler marking every a wavelength and the voltage V_α is regarded as a ruler with scales smaller than a wavelength. The calibration of the ruler produced by the voltage V_b can be made automatically with the double feedback control by changing the OPD at intervals of approximately a wavelength.

3 Signal Detection with a CCD Image Sensor

A linear CCD image sensor is used to measure step-surface profiles as shown in Fig. 1. The CCD image sensor detects a distribution of interference intensity on a number of cells at intervals of the integration time T_A, as shown in Fig. 3. The number of the cells on which intensity is detected is N. The intensity on a specified cell is sampled and held within the integration time T_A. This sample-hold is repeated N_R times, so that an interference signal whose length is $T_m = N_R T_A$ is obtained for one measuring point. This generation of the interference signal is shown in Fig. 3, where number of the specified cell is 1. After detection on a specified cell, the point of the sample-hold is moved to the adjacent cell to scan the measuring points.

The integration time T_A is taken to be T_b/p, where $T_b = 1/f_b = 2\pi/\omega_b$, and p is an integer. The CCD image sensor integrates $S_D(t) = S(t)I_M(t)$ over the period of T_A and outputs the integrated value $S_C(t)$, as shown in Fig. 1. At the same time the PD detects $I_M(t)$, and the integrated value is divided by $I_M(t)$. This division process provides integration values $S_I(t)$ of $S(t)$ on the assumption that $I_M(t)$ is almost constant within the period of T_A. Integer p is taken to be 16 or 32 to satisfy this assumption. Then p integration values of $S(t)$ are obtained during one period of T_b. The amplitude of frequency component of nf_b contained in the integration values of $S(t)$ is attenuated by coefficient of $\sin[(n/p)\pi]/[(n/p)\pi]$ compared to that contained in $S(t)$, where n is an integer.[5] Since feedback signal A_1 is generated from frequency component of $2f_b$, the amplitude of A_1 is decreased by this attenuation due to the integral detection of the CCD image sensor. However, there is no bad effect because the attenuation of $n=2$ is 0.97 at $p=16$.

Feedback signal A_2 is obtained from the difference between the two integration values of $S(t)$ produced during the period of T_A whose central positions in time satisfy $\cos \omega_b t = 1$ and $\cos \omega_b t = -1$, respectively. In this case feedback signal A_2 is given by

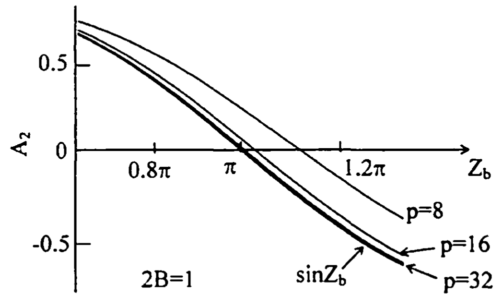

Fig. 4 Feedback signal A_2 when the integration time T_A is T_b/p.

$$A_2 = 2B \sum_{n=0}^{\infty} (-1)^n J_{2n+1}(Z_b) \frac{\sin[(2n+1)(2\pi/p)]}{(2n+1)(2\pi/p)}. \tag{8}$$

When p is infinite, Eq. (8) becomes $2B \sin Z_b$, which is generated in the detection with a photodiode. Figure 4 shows the values of Eq. (8) for different values of p, where $2B=1$, compared to $\sin Z_b$.

4 Experiments

4.1 *Fundamental Characteristics*

An interferometer for real-time step-profile measurement shown in Fig. 1 was constructed. Central wavelength λ_0 and spectral bandwidth of the SLD were 788.7 and 20 nm, respectively. A 1200-line/mm holographic grating was used for G_1 and G_2. The focus length of lenses L_1 and L_2 was 25 mm, and the width of slit SL was about 100 μm. The frequency $f_b = \omega_b/2\pi$ was 400 Hz.

We tried to detect the stable points of V_b, where a PD was used instead of the CCD image sensor. Gauge blocks fixed on a stage was used as an object. We displaced the object with a micrometer to change the OPD. By increasing the OPD at intervals of approximately one wavelength, we could move a stable point of V_b to the next point sequentially. We detected 83 stable points of V_b whose order is denoted by the number N of 0 to 82, as shown in Table 1.

We tried to determine integer m corresponding to number N. We converted stable points of V_b shown in Table 1 into values of b with the relation of $b = 1.59V_b + 0.059$, and obtained measured values of $L_Z = \lambda_0^2/2b$. The values of m_c were calculated from the measured values of L_Z using Eq. (6). Since the absolute value of the difference was less than 0.5 in the region of $N=20$ to 70, we could determine the values of integer m. From this result, the relation of $m = 46+N$ was obtained, as shown in Table 1. The measurement range was from 36 to 101 μm in the OPD.

4.2 *Step-Profile Measurement*

We tried to measure a step profile that was made by sticking two gauge blocks of different thickness together. We changed the value of p and made the measurements. When $p=8$, the feedback control of V_α was unstable because

Table 1 Stable points of V_b and integer m.

N	V_b	m	N	V_b	m	N	V_b	m	N	V_b	m	N	V_b	m
0	4.86	46	17	3.80	63	34	3.05	80	51	2.51	97	68	2.13	114
1	4.78	47	18	3.75	64	35	3.02	81	52	2.48	98	69	2.12	115
2	4.68	48	19	3.70	65	36	2.98	82	53	2.46	99	70	2.10	116
3	4.59	49	20	3.66	66	37	2.94	83	54	2.44	100	71	2.08	117
4	4.53	50	21	3.61	67	38	2.91	84	55	2.41	101	72	2.06	118
5	4.46	51	22	3.57	68	39	2.87	85	56	2.39	102	73	2.05	119
6	4.39	52	23	3.52	69	40	2.84	86	57	2.37	103	74	2.04	120
7	4.33	53	24	3.48	70	41	2.81	87	58	2.34	104	75	2.02	121
8	4.27	54	25	3.43	71	42	2.77	88	59	2.32	105	76	2.01	122
9	4.20	55	26	3.38	72	43	2.74	89	60	2.29	106	77	2.00	123
10	4.14	56	27	3.33	73	44	2.71	90	61	2.27	107	78	1.99	124
11	4.09	57	28	3.29	74	45	2.68	91	62	2.25	108	79	1.98	125
12	4.03	58	29	3.25	75	46	2.65	92	63	2.23	109	80	1.96	126
13	3.98	59	30	3.21	76	47	2.62	93	64	2.21	110	81	1.95	127
14	3.93	60	31	3.17	77	48	2.59	94	65	2.19	111	82	1.93	128
15	3.88	61	32	3.13	78	49	2.56	95	66	2.17	112			
16	3.84	62	33	3.09	79	50	2.53	96	67	2.15	113			

$I_M(t)$ was not regarded to be almost constant within the period of $T_A = T_b/8$. When $p = 32$, the measurement was impossible because the amplitude of the interference signal detected with the CCD image sensor was too small. The most appropriate value of p was 16. Since a low-pass filter with cutoff frequency of $f_b/10$ was used to generate the feedback signal A_1 from the integration values of $S(t)$, measuring time of $T_m = N_R T_A$ for one measuring must be longer than $10T_b$. This means that number of the repetition N_R is must be more than 160 at $p = 16$. When $N_R = 128$, the feedback control of V_α was unstable. When $N_R = 512$, the measurement results were almost the same as $N_R = 256$. Therefore the most suitable condition was that $p = 16$, $N_R = 256$, and $T_m = 0.04$ s. Number of the measuring points N was 17, and the interval of measuring points was 119 μm on the object surface.

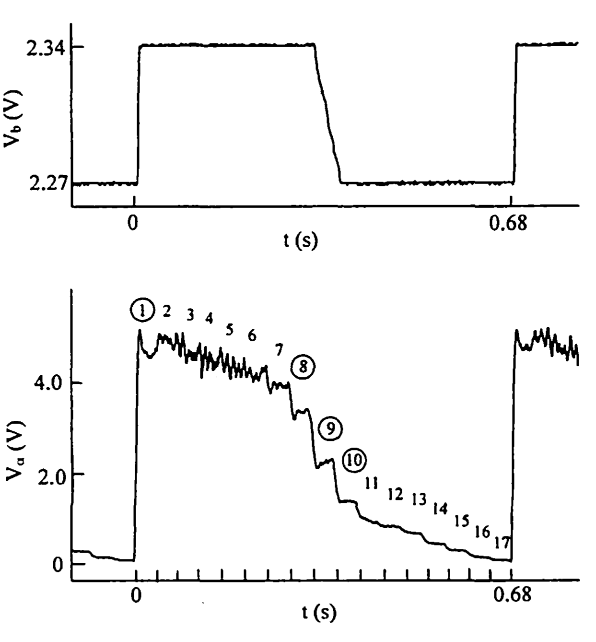

Fig. 5 Detected signals of V_b and V_α for step height of 1 μm.

The step height in the two gauge blocks stuck together was 1 μm. We detected signals $V_b(t)$ and $V_\alpha(t)$, as shown in Fig. 5. Number of the cell that represents the position of the measuring point is indicated above the signal of $V_\alpha(t)$. The number surrounded with a circle means the measuring point where exact measurement did not made. Table 2 shows the measured values at cells 5 to 13. The values of m were determined with Table 1, and the values of $L_\alpha(t)$ were calculated with relationship $L_\alpha = \beta V_\alpha$, where $\beta = 83.37$ nm/V. Exact measured values could not be obtained at cells 8 to 10 around the boundary of the two gauge blocks. When the measuring point returned to the first measuring point (cell 1) from the last one (cell 17), exact measurements also could not be made at cell 1. The measured height of the step between cells 7 and 11 was 1.061 μm. The feedback control of V_α was sensitive to the amplitude of the interfer-

Table 2 Measured values for step height of 1 μm.

Cell No.	V_b (V)	V_α (V)	m	L_α (nm)	L (nm)
5	2.34	4.31	104	359	82758
6	2.34	4.13	104	344	82743
7	2.34	3.98	104	332	82731
8	2.34	3.35	104	279	82678
9	2.29	2.28	106	190	84173
10	2.27	1.61	107	134	84910
11	2.27	0.92	107	77	84853
12	2.27	0.78	107	65	84841
13	2.27	0.69	107	50	84826

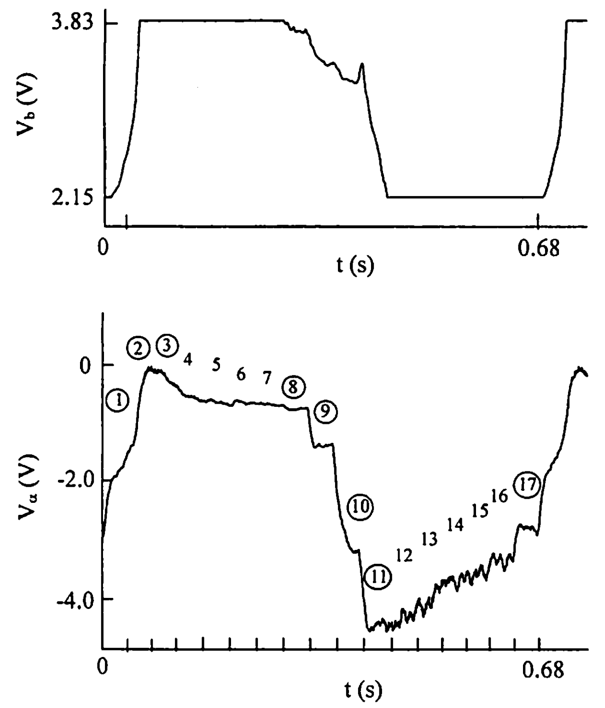

Fig. 6 Detected signals of V_b and V_α for step height of 20 μm.

ence signal. When the amplitude of signal A_1 was not suitable to feedback controller FC1, a large fluctuation occurred in the signal of V_α between cells 3 and 6, as shown in Fig. 5. The measurement error caused by fluctuations of V_α was estimated to be less than 8 nm. Next we measured a step profile with a step height of 20 μm. The results are shown in Fig. 6 and Table 3. Compared with the results shown in Fig. 5, a longer time was required to reach the stable values of V_b and V_α when the measuring point returned to the first measuring point from the last one. The effect of the boundary of the two gauge blocks also became stronger. The measured height of the step between cells 7 and 12 was 20.053 μm.

Table 3 Measured values for step height of 20 μm.

Cell No.	V_b (V)	V_α (V)	m	L_α (nm)	L (nm)
5	3.38	−0.67	62	−56	49067
6	3.38	−0.69	62	−57	49066
7	3.38	−0.70	62	−58	49065
8	3.66	−0.81	66	−68	52224
9	3.29	−1.37	74	−114	58516
10	3.09	−3.19	79	−266	62326
11	2.65	−4.44	92	−370	72522
12	2.15	−4.30	113	−357	89171
13	2.15	−4.04	113	−337	89192
14	2.15	−3.71	113	−309	89220

5 Conclusion

The linear CCD image sensor was used to measure I-D step profiles in real time with the SWS interferometer using double feedback control. The OPD and the amplitude of the SWS were controlled with the feedback signals that were generated from the integration values of the interference signal detected by the CCD. It was made clear that the most appropriate integration time of the CCD was 1/16 of one period of the SWS. Two different step profiles with a step heights of 1 and 20 μm, respectively, were measured with the measurement error less than 8 nm. The measuring time for one measuring point was 0.04 s, and the number of the measuring points was 17.

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