A High Precision Diffraction-Interferometry Stylus Probing System

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Abstract

In this paper, a stylus probe system based on the principle of diffraction-interferometry is presented for surface profile and roughness measurements. A reflective cylindrical holographic diffraction grating fabricated into cylindrical shape acts as a length scale. The surface profile information was transformed into electrical signals using a laser diode grating interferometer to measure the rotation motion of the measuring lever. The phase-shift interpolating technique is proposed to achieve 32- subdivision of the grating constant for enhancing the system resolution. A resolution of 25 nm and non-linearity of ± 0.1% in the long measuring range of ± 2.5 mm can be achieved analytically and experimentally. Practical applications for height and roughness measurements are also presented.

1. Introduction

Surface metrology plays an important role in precision manufacturing. According to the characteristics of measuring principle, the surface topography measurement can be categorized into three forms, the most popular stylus method [1-3], optical method using various interferometries [4-6], and scanning probe microscopic method (SPM) for nano-metrology [7,8]. It has been a long history using the inductive pick-up for topography detection in the industry. In the last decade, the laser interferometric pick-up unit was developed by Rank Taylor Hobson Co. to nanometric resolution with long traverse length [9]. Due to the employment of a He-Ne laser interferometer, however, its size is still bulky.

In this paper, a stylus probe using a laser diode interferometric transducer has been developed, which can be applied to surface texture, form error, radius, inclination, and dimension measurements. A RCDG (Reflective Cylindrical Diffraction Grating) fabricated into cylindrical shape, referred to as the “length scale”, acts as the moving part [10-12]. The photo detection system for interference signals capturing and the corresponding signal process algorithms are developed. A resolution of 25 nm and non-linearity of ± 0.1% in the long measuring range of ± 2.5 mm can be achieved analytically and experimentally. The advantages of the probe are compact, interchangeable among measuring devices, easy for construction and inexpensive.

2. Measurement Principle

The key components of the developed system are: reflective cylindrical holographic diffraction grating (RCDG), stylus mechanism, laser diode, photo diode, interference fringe transformation algorithm, and signal processing circuit.

2.1The Reflecting Cylindrical Diffraction Grating

A specific design for the developed stylus probe is to use a reflecting cylindrical diffraction grating (RCDG) as a displacement transducer component. Because of the special requirement of broad dynamic measuring range to resolution for topography, the interferometric displacement measurement system adopts reflecting cylindrical diffraction grating transducer according to the principle of Doppler effect. The general concept of the stylus probe is shown in Figure 1.

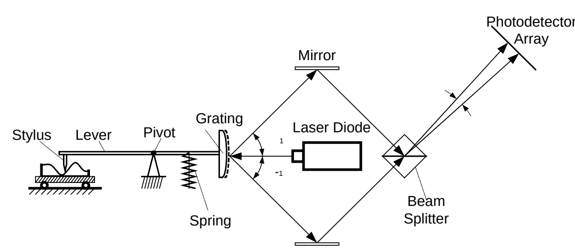

Figure 1: Schematic Diagram of the Stylus Probe System

The measuring lever is pivoted at the knife bearing. The spring provides recovering force for knife bearing to maintain the centering of the lever and measuring tip induces a stylus force. The RCDG is fixed rigidly to the tail of the lever. The center curvature axis of the RCDG is coincident with the axis of rotation of the level. The holographic line phase reflecting grating, fabricated on the surface of the cylinder, performs as the length scale for the displacement transducer. A specially designed and fabricated prism combines the two ±1st order diffraction beams to create a fringe pattern to the photo detector, as shown in Figure 2.

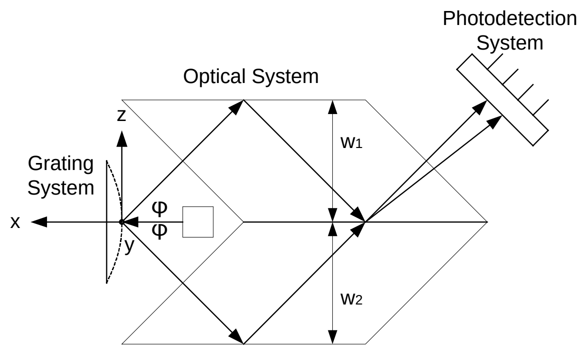

Figure 2: Optical prism and optical path for RCDG System

Frequency shift of the ±1st order diffraction beams according to Doppler effect will occur as soon as the tip moves. The actual frequencies of the two diffraction beams can be derived as

$$\begin{cases} f_{+1} = f_0 + \dfrac{v}{d_g} \\ f_{-1} = f_0 - \dfrac{v}{d_g} \end{cases} \tag{1}$$

where f_0 is the frequency of incident light,
f_{+1} is the frequency of the +1st order diffraction beam,
f_{-1} is the frequency of the -1st order diffraction beam,
v is the vertical velocity of the measuring tip and grating,
d_g is the grating constant.

Thus, the interference fringes, created in the photo detector array, move as well because of the beating frequency shown as follows.

$$\Delta f = f_{+1} - f_{-1} = 2\frac{v}{d_g} \tag{2}$$

The magnitude of the beating signal received by each element of photo detector array can be obtained as

$$I(t) = I_1 + I_2 \cos\left(2\pi \int_0^t \Delta f dt\right) = I_1 + I_2 \cos\left(4\pi \frac{\Delta z}{d_g}\right) \tag{3}$$

where, t is time and the upper limit of integration is beating signal period T,
$4\pi \frac{\Delta z}{d_g}$ is the phase shift due to beating signal when Doppler effect occurs,
I_1, I_2 is the magnitude of DC and AC term of the received signal, respectively.

The drift velocity of the fringe is proportional to the vertical velocity of the measuring tip. A period alteration of the fringe alters the beating signal for a cycle. The phase shift for a cycle is equal to 2π and the relationship of signal and geometry variation can be expressed as

$$2\pi = 4\pi \frac{\Delta z}{d_g} \tag{4}$$

Thus, the displacement of the grating due to the movement of the measuring tip and the quantities of pulse due to phase shift from beating signal are correlated as $\Delta z = \frac{d_g}{2}$. As a result, a signal with two sine-wave periods per grating pitch is obtained from each element of the photo detector array. The photo detector array then converts the interference fringe pattern into a set of four sinusoidal signals that are differing in phase by π/2 with each other along the detected moving direction. With appropriate signals processing circuits, the displacement can thus be appropriately measured and quantified by counting the fringe drifting and calculating the interpolation value of the sinusoidal signals to deduce the workpiece profile. Figure 3 shows the signal processing flow diagram.

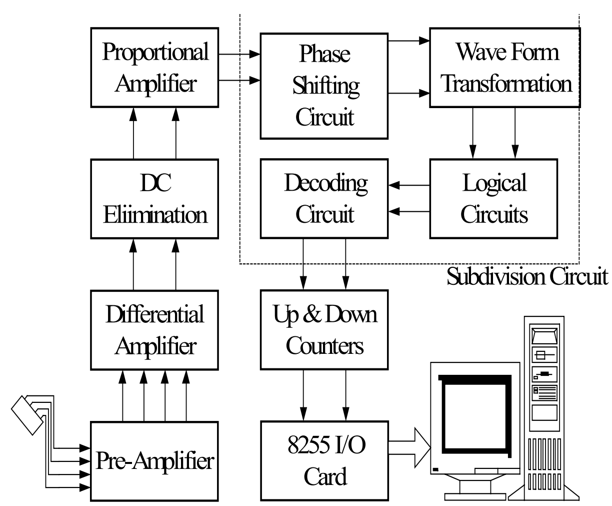

Figure 3: The Signal Processing Flow Diagram

2.2 Stylus Design

The requirement of steady reaction force and robust dynamic characteristics of the profiling stylus mechanism is important. The measuring tip should surely come into contact the measuring surface being measured throughout a measuring process. A reactive stylus force is used as a special design for the probe mechanism, as shown in Figure 4. There are three constraints that should be satisfied.

1. The natural frequency of the system should be greater than the vibrational frequency of the lever during a measuring process.
2. The stylus force should satisfy the international standard.
3. The eccentricity of the bearing should be minimized.

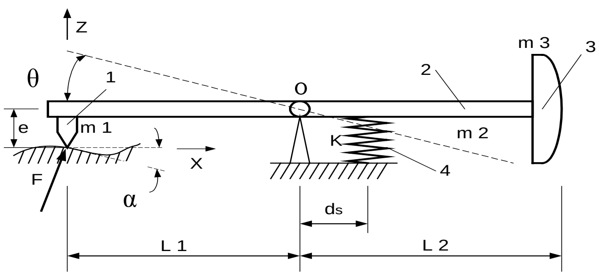

Figure 4: Schematic Diagram of the Stylus Mechanism

1 is the stylus,
2 is the lever,
3 is the RCDG grating,
4 is the leaf spring,
d_s is the leaf spring offset distance,
F is the stylus reaction force,
g is the gravitational constant,
K is the leaf spring constant,
L_1 is the fore end length of the lever,
L_2 is the rear end length of the lever,
m_i is the mass of the component i; $i = 1\sim3$,
θ is the cw rotational angle of the lever,
α is the inclination of the measuring surface along measuring path direction.

To achieve the excellent centering of the bearing, the specific knife bearing method is adopted for the design of pivot. The probe system, which is made of measuring tip, lever, knife-edge bearing, and clamping spring, is rigidly mounted on an aluminum base, as shown in Figure 5.

The following condition must be achieved.

$$w_n > w_v = w_i \cdot v_s \tag{5}$$

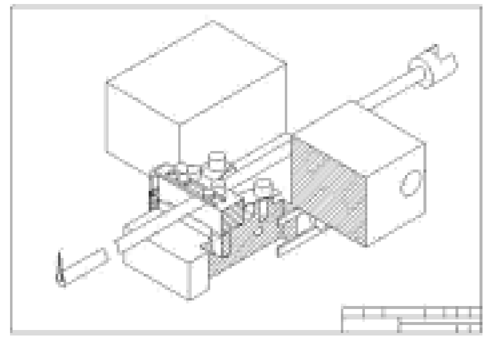

Figure 5: CAD Drawing of the Stylus System

where w_v is the resonant frequency of the lever,
w_i is the spatial frequency of the measuring surface,
v_s is the scanning velocity.

Depending on the spatial frequency requirement, the scanning velocity limit is derived as, $v_s < \frac{\omega_n}{\omega_i}$. The spatial frequency that can be detected by the contact stylus depends on the radius of the stylus tip. The radius of the stylus tip adopted in the prototype of the profiling head is 10 μm so that the cut-off wavelength, the minimum spatial wavelength that can be detected, is set to twice the radius as 20 μm. The spatial frequency can be calculated as

$$\omega_i = \frac{2\pi}{\lambda} = \frac{2\pi}{20\mu m} \approx 0.31416 \ {}^{1}\!/_{\mu m} \tag{6}$$

From experiment the resonant frequency of the lever was found with 169 Hz. The scanning velocity limit can then be evaluated as

$$v_s < \frac{\omega_n}{\omega_i} = \frac{169Hz * 2\pi}{\pi /_{10\mu\, m}} = 3380\mu\, {}^{m}\!/_{s} \approx 3.34\, {}^{mm}\!/_{s}$$

Thus, the maximum scanning velocity can be set as 3 mm/s.

2.3 The Photo-detection System

In this study, the photodiode array is used to detect the interference fringe pattern. The amplitude of illumination distribution of interference pattern, along the direction perpendicular to the fringe, is sinusoidal and should be tuned to fit to the size of photodiode element. To get output signals in orthogonal sinusoidal waves, the geometry of the photodiode array elements are placed relative to the interference patterns in such way, as shown in Figure 6, that photo-detector element PD_1 detects fringe of first interference order.

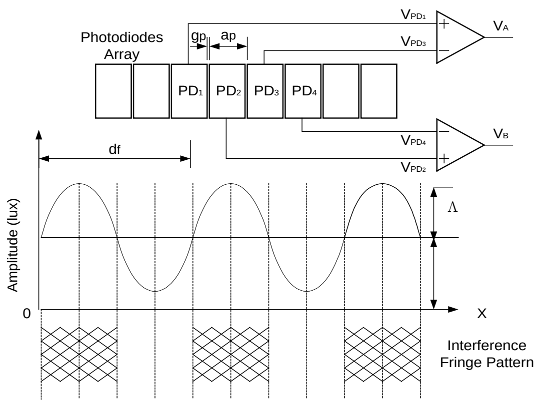

Figure 6: Photo Detector System Scheme

Under the assumption that d_f = 4a (the fringe constant is quadruple of the photodiode's), the output current of each photodiode is proportional to the optical power received by each element and the output signals of each photo-detector through out the operational amplifier are

$$V_1 = V_{o1} + V_1^{'} \sin\theta; \quad V_2 = V_{o2} + V_2^{'} \cos\theta; \qquad (7)$$

$$V_3 = V_{o3} - V_3^{'} \sin\theta; \quad V_4 = V_{o4} - V_4^{'} \cos\theta;$$

where $\theta = \frac{-3\pi}{4} + 2\pi \Delta f t$,

V_{oi} is the DC part of signal V_i; i = 1~4,

$V_i^{'}$ is the amplitude of signal V_i.

The photo-detector array converts the interference fringe pattern into a set of four sinusoidal signals in phase difference of π/2.

2.4 Sinusoidal Signals Subdivision

Traditional signal processing techniques such as interpolation of orthogonal sinusoidal waves to enhance the resolution, quarter subdivision, AD technology, and special designed interpolator can be further modified for nano-metrology. In this study, subdivision of sinusoidal signals by continuous phase shifting was adopted to enhance the resolution of interferometric transducer for developed stylus probing system.

For quarter subdivision that decodes a period of two orthogonal sinusoidal waves into 4 pulses. Using sin(θ), sin($\theta + \pi/2n$), sin($\theta + 2\pi/2n$) ~ sin($\theta + (n-1)\pi/2n$), these n signals can subdivide and decode a period of orthogonal sinusoidal waves into $N = 4n$ pulses as follows.

$$N = 4n = \frac{2\pi}{pd}$$

where N is the subdivision number;

pd is the least phase difference of the adjacent synthetic sinusoidal waves.

In the signal processing, the synthetic phase shifted signal can be obtained by using operational amplifier circuits. Adjusting the gain of operational amplifier by tuning the resistance, equal amplitudes of four different phase signals, sin(θ), sin($\theta + \pi/2n$), sin($\theta + 2\pi/2n$) ~ sin($\theta + (n-1)\pi/2n$), can be achieved. Using those signals, a period of orthogonal sinusoidal waves can be subdivided and decoded into $4n$ pulses. Thus, a general form of phase shifting can be derived as

$$\sin(\theta+\phi)+\sin(\theta+\phi-\frac{\pi}{2^{n+1}}) \qquad (8)$$

$$= 2\cos(\frac{\pi}{2^{n+2}})\cdot\sin(\theta+\phi-\frac{\pi}{2^{n+2}})$$

where $\varphi = \frac{k\pi}{2^{n+1}}$; n is the order of phase shifting; $k = -2^n \sim 2^n$.

Adopting logical operation of converted rectangular signals, a general form of effective multiple frequency rectangular signals can be derived as

$$f(sin(2^n\theta+\varphi)) \oplus f(sin(2^n\theta+\frac{\pi}{2})) = f(sin(2^{n+1}\theta+\varphi)) \qquad (9)$$

where ⊕ : exclusive or (XOR) and

$$f(sin(\theta)) = \begin{cases} 1, 2k\pi \le \theta \le (2k+1)\pi \\ 0, (2k-1)\pi < \theta < 2k\pi \end{cases} ; \; k \in Z$$

The relations among phase shifting order, phase difference, subdivision number and resolution can be established as shown in Table 1.

Table 1 Resolution of Phase Shifting Order

Phase shifting order	Phase difference	Subdivision number (N)	Resolution ($d_g/2N$)
0	π/2	4	$d_g/8$
1	π/4	8	$d_g/16$
2	π/8	16	$d_g/32$
n	$\pi/2^{n+1}$	2^{n+2}	$d_g/2^{n+3}$

The measuring system, adopting reflective cylindrical holographic grating as an interferometric transducer, essentially resolves to half of the grating constant, i.e. $d_g/2$. Taking subdivision technique with $N = 2^{n+1}$, adopting phase shifting of order n, it enhances the resolution to $d_g/2^{n+2}$. For a grating constant d_g = 0.8333 μm and using 16-subdivision technique, the resolution evaluation can be calculated as

$$\frac{d_g}{2N} = \frac{0.8333}{2 \times 16} = 0.026042\mu\, m \approx 26nm\,.$$

3. System Calibration

To validate the reliability of the developed signal processor of the stylus probe system, an experiment was conducted to test and calibrate the measuring range and linearity. The experiment adopts HP 5529 laser interferometer to calibrate the profiling head. The experiment setup is shown in Figure 7. The retro-reflector was attached to a fixture that was setup on the worktable. The fixture/worktable was moved back and forth to mimic the surface profile variation. The corresponding stylus motion was sensed by the RCDG displacement transducer and processed by the signal processor. The same motion was sensed by the laser interferometer. The experiment was performed 6 times. The outputs of the HP laser interferometer and developed system were analyzed and compared. The data comparison is presented in Figure 8 and non-linearity is shown in Figure 9. It was found that there is only ± 2.5 μm non-linearity error in the full scale range of ± 2.5 mm, i.e. 0.1%.

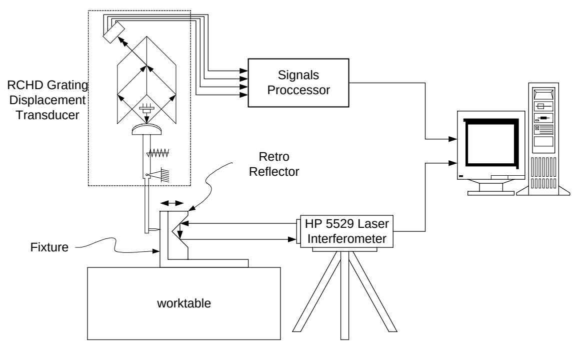

Figure 7: Experiment of Accuracy Calibration

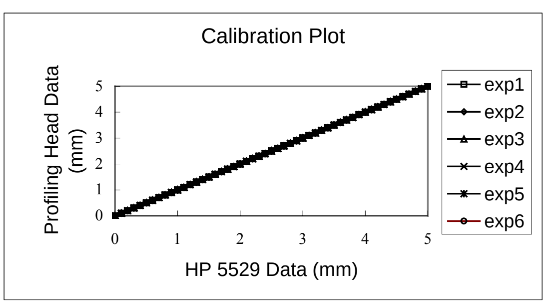

Figure 8: Comparison Plot of Profiling Head and HP 5529 system

4. Applications

To further illustrate the application of the developed stylus probe system, two experiments were conducted to measure surface characteristics and compare with the standard values.

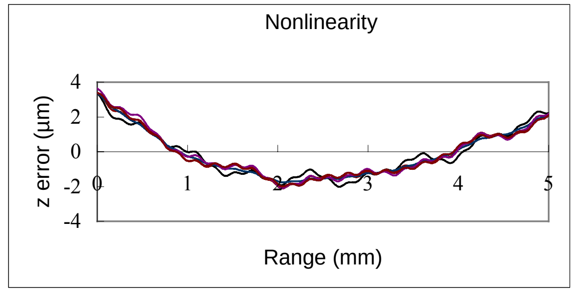

Figure 9: Experiment Data Non-Linearity Plot

4.1 Gauge Blocks Height Measurement

Several gauge blocks were combined to form two step-surface sets. In Figure 10, three gauge-blocks with the dimension of 1.004 mm, 1.002 mm and 20 mm were combined to form two planes with a 2-μm step.

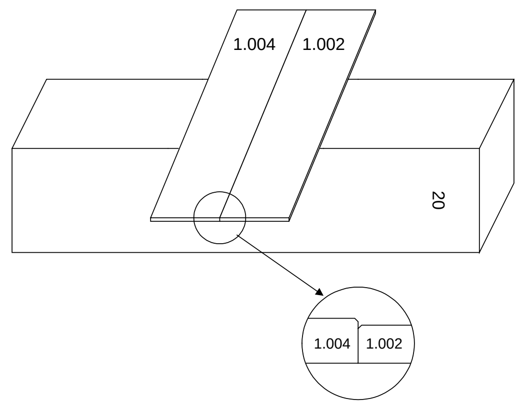

Figure 10: Gauge Blocks Set with 2μm Step

The experiments were performed three times and the results are presented in Figures 11. By least squares fitting of the two parallel lines, the distance between the upper and lower lines can be calculated to the average value of 2.049μm with data scattering < 1 nm.

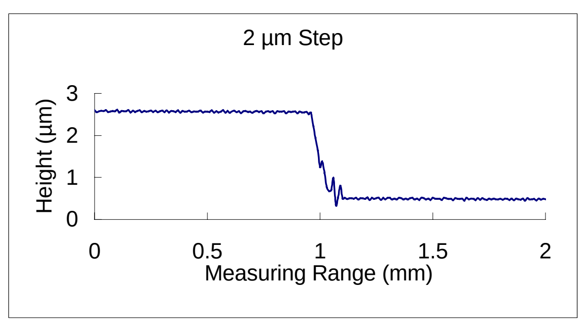

Figure 11: Measurement of 2 μm Step

4.2 Roughness Measurement

The reference specimen adopted for roughness measurement is a Type 1121107 of Rank Taylor Hobson

Co. with R_a = 6.07 µm. The experiment was performed 5 times and sampled 5 zones each time. The local microscopic profile is shown in Figure 12.

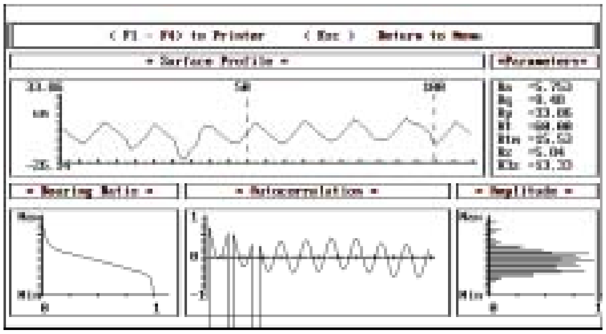

Figure 12 Specimen Roughness Measuring Result

In order to test the reliability and performance, a commercial product, Pocket Surf roughness-meter made by Federal Co., was adopted to measure the same specimen. The nominal value of R_a is 6.07 µm. The measured value of the developed system was R_a = 5.753 µm with a standard deviation (SD) = 0.023 µm. Measured by the Pocket Surf, R_a = 5.761 µm with a SD = 0.047 µm.

5. Conclusions

A stylus probing system using the interferometric transducer, which can be applied to all kinds of devices for surface texture, form error, radius, inclination, and dimension measurement, has been developed. A RCDG (Reflective Cylindrical Diffraction Grating) interferometer that acts as the length master is adopted instead of the laser interferometer. The photo detection system for interference signals capturing and the corresponding signal process algorithms are developed. The advantages of the probe are compact, interchangeable among measuring devices, easy for construction and inexpensive.

Because of the grating acting as a length master instead of the wavelength for displacement measurement, the need of stabilizing the frequency and compensation of the light source can be avoided. The specifications of the adopted low-cost laser diode are 670 nm of wavelength and 5mw of power. The major energy of the $\pm 1^{st}$ order diffraction beams are adopted as measuring signals. The grating constant d_g (0.8333 µm with 1200 gratings per mm), which is selected according to the wavelength of laser diode, diffraction order and the resolution requirement of the system, is the most important parameter of the measuring system because of its role as the length master.

The development of electrical devices for converting the interferometric signal into digital signals is also discussed. The phase-shift interpolating technique is adapted to enhance the system resolution to nm scale. Experimental applications for height and roughness measurement are also presented.

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