A Diffraction Grating Scale for Long Range and Nanometer Resolution

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ABSTRACT

This paper presents a novel design of a laser linear encoder based on the principle of diffractive interferometry. It adopts a special design in optical path that can increase the alignment tolerance between the optical head and the grating. Because of the simple optical configuration and the merit of compact size, it can effectively reduce the environmental disturbance and allow higher stability. In addition, the signal process circuit can effectively decrease three major errors: the DC shift difference, the electronic gain difference and the phase orthogonal error of two sinusoid al output signals. The resolution can reach to 1nm. Experiment results showed the standard deviation was below 17nm for 15mm travel in normal laboratory environment.

Keywords: Linear encoder, diffraction gratings, interferometer, nanometer resolution

1. INTRODUCTION

In the development for micro/nano technology, many nano-scaled manufacturing and measuring systems adopt capacitance sensor to measure nanometer displacement, but the measuring range is limited. However, sensors with long measuring distance and high resolution, such as laser interferometer, are expensive and subjected to be affected by unstable environment. Thus the need of compact, high resolution, high stability and easy-to-use displacement sensor or is becoming more indispensable.

The displacement measurement of interference technique of grating has been widely used. Ishii and Nishimura proposed a radial grating which can detect diffraction light and modulate intensity of light source[1]. Sawada used lithography method to develop an extremely small integrated microencoder whose size is less than 1mm long[2]. Lee used aberration compensation method to correct the wavefront of diffraction light in laser encoder[3].

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Wu developed a new laser encoder system which includes a telescope design and diffraction efficiency optimized grating[4]. Nishimura and Kubota proposed an optical structure which avoids zero-order diffraction light on photodetector[5]. Chen proposed a newly compact laser encoder which has high tolerances and repeatability below 29.9nm[6].

In order to reach high resolution, high stability and compact laser diffraction encoder, we propose a novel optical design which has simple optical configuration and high alignment tolerance.

2. MEASUREMENT PRINCIPLE

The proposed optical configuration of linear diffraction grating interferometer (LDGI) is shown in Figure 1. The optical system employs polarization technique to obtain clear and low noised two sinusoidal waveforms. The laser diode emits a linearly polarized beam with 635nm wavelength. The beam is split by a polarization beam splitter (PBS) with equal intensity. The P-polarized beam is reflected twice by a Rhomboid prism (RHP), and then propagates along the right side of the optical path. The quarter waveplate (Q2) converts the P-polarized beam into a right-circular polarized light beam. Simultaneously, the S-polarized beam is reflected by a right angle prism (RAP), and then propagates along the left side of the optical path, and is then converted into a left-circular polarized beam after Q1. These two circularly polarized light beams are reflected by mirrors 1 and 2 respectively, and diffracted by the holographic grating. With the emitted angles equal to the grating's ±1 diffraction angles, the input beams will be diffracted back through the same paths to mirrors 1 and 2, respectively. The left-arm beam is changed to a P-polarized beam after it transmits through Q1. Similarly, the right-arm beam is changed to an S-polarized beam after it transmits through Q2. After two beams passing through the quarter waveplate Q3 they would be retarded to the left-circularly polarized and right-circularly polarized beams, respectively. The NPBS divides both the right-circularly and the left-circularly polarized beam into two split beams of equal intensity. These four beams will be divided into 0-90-180-270 degrees by PBS2 and PBS3 (set fast axis to 45 degrees) and interfere with each other. These four orthogonal signals are detected by PD1 to PD4, respectively, arranged in four different azimuth angles. Analyzed by Jones vector, the intensity of each photodetector can be expressed as:

$$
\begin{aligned}
I_{PD1} &= A\left[1-\sin\left(2\Delta\omega\cdot t\right)\right] \\
I_{PD2} &= A\left[1+\sin\left(2\Delta\omega\cdot t\right)\right] \\
I_{PD3} &= A\left[1+\cos\left(2\Delta\omega\cdot t\right)\right] \\
I_{PD4} &= A\left[1-\cos\left(2\Delta\omega\cdot t\right)\right]
\end{aligned} \tag{1}
$$

A grating scale displacement of Δx causes a double Doppler shift which is related to the phase difference of the first order diffraction by the following equation:

$$\Delta\omega = 4\pi \frac{\Delta x}{d} \qquad (2)$$

where, d is the grating pitch. The phase difference between these two beams depends on the position of the grating. As the grating moves, the phase relationship of these two beams changes causing to the constructive or destructive interferogram. By Equation (2), the period of the interfering beams within the encoder is d/2. With proper signal interpolation of the quadrature signals, the measuring resolution of the laser encoder system can easily reach to 1 nm resolution with a grating pitch of 0.833μm. The real dimension of optical structure is $55x32x30mm^3$.

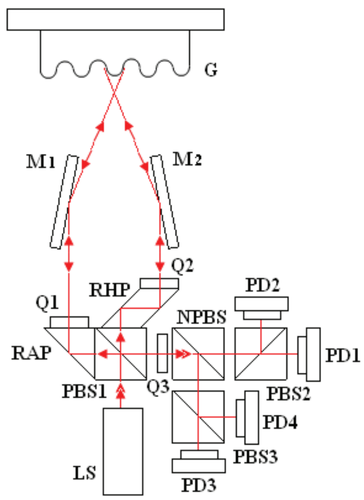

Fig.1. Principle of linear diffraction interferometer (LS: laser diode, G: grating, PBSi: ith polarizing beam splitter, RAP: right angle prism, RHP: rhomboid prism, Mi: ith mirror, NPBS: non-polarizing beam splitter, Qi: ith quarter waveplatei, PDi: ith photodetector.)

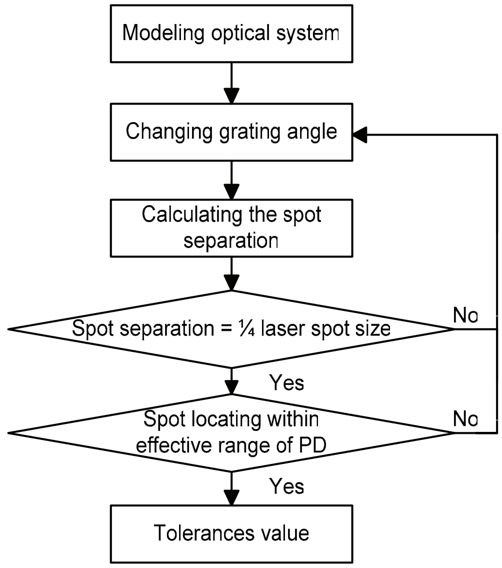

Fig.2. The procedure of head-to-scale alignment tolerances analysis.

The performance of LDGI is based on the quality of interference signals. We adopt two criteria to evaluate the head-to-scale alignment tolerances. (1) The spot separation must be less than quarter diameter of the laser spot, and (2) The laser spot must be located within the effective range of each photodetectors. The procedure of alignment tolerances analysis is shown in Figure 2. The result of the alignment tolerances is calculated by the LightTools^{TM}, as shown in Table 1. It is clearly seen that the alignment tolerances have two excellent tilt tolerances (yaw and roll) and two distance tolerances (standoff and offset) between the optical head and the linear gratings because of this special design of optical path.

Table 1: Allowable tolerance of the head to scale motion

Motion	Values
Yaw (degree)	±1.15
Roll (degree)	±1.25
Pitch (arc min)	±16
Standoff (mm)	±4
Offset (mm)	±4.5

3. EXPERIMENT AND RESULTS

The diagram of measurement system is shown in Figure 3. The linear diffraction grating is mounted on the precision moving stage. The stage is driven by the ultrasonic motor (HR4 of Nanomotion Co.). The light signals received by 4 detectors are converted into voltage signals by a signal processing circuit, and then sent into the high-speed, multi-channel data acquisition card, and finally interpolated by the LABVIEW program.

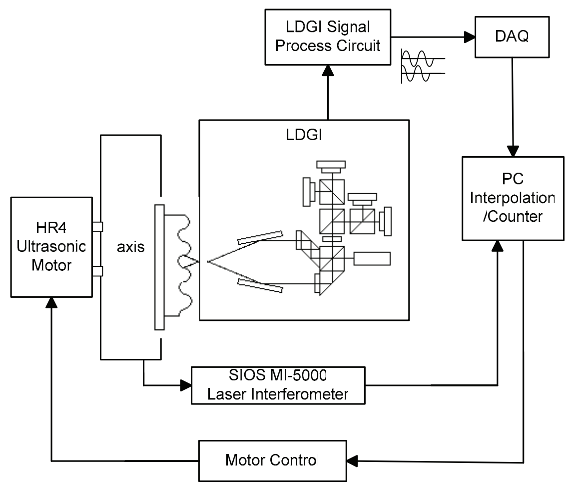

Fig.3. The diagram of measurement system.

In classical orthogonal waveforms there are three major error sources. As described by Heydemann[7], these are:

1. Lack of quadrature (the phase shift between two signals is not exactly λ/4 or π/2),
2. unequal gain in the detector channels, and
3. zero offset.

To correct the first error, it is possible to use a vector summation and subtraction operation in order to obtain the exact orthogonal waveforms. The second error should be corrected by a filtering process using an electronic circuit or by software. The third error can be corrected by using differential signals. Fig. 4 shows the circuit diagram of LGDI signal process. This signal process was implemented by a FPGA hardware board (Altera DE2) with sampling frequency 60MHz and internal operating frequency 50MHz. The data transfer rate can be easily achieved to 4MHz, which is adequate enough to cope with the moving speed of the gratings at 2mm/second. Detailed design of the FPGA by VERILOG language is not included in this report. Fig. 5 plots the corrected waveform (upper) and the Lissagous diagrams before and after the error compensation (lower). Since one wave cycle corresponds to 416 nm of the grating displacement, we can easily reach a 1 nm resolution after a signal subdivision of 400 interpolated signals. The dimension is only about 55mm x 40mm x 30mm. It is easily equipped into a small nanopositioning stage.

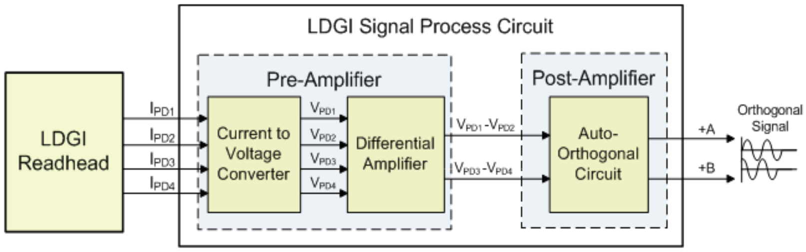

Fig.4 Diagram of LDGI signal process circuit.

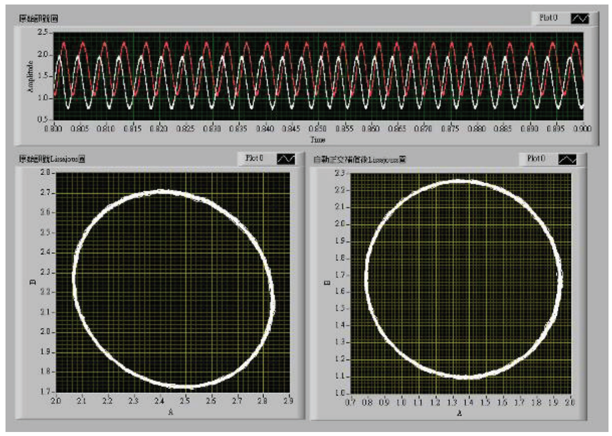

Fig.5. The Lissajous plots before and after error compensation.

The experimental setup is shown in Figure 6. The motion of the linear stage, detected by the LDGI system, is calibrated by the miniature laser interferometer made by SIOS Co. The operational principle of the ultrasonic motor HR4 is shown in Figure 7 in which the tip is deliberately separated from the slide to show its elliptical motion form[8]. This cyclic motion is called the AC mode motion with minimum step of 5nm. This ultrasonic motor also features a DC mode motion actuated by a DC voltage, which is proportional to even finer motion within 5 nm. Since the motor is tiny and easy to control it is suitable to small nanostages. For the long travel test, the motion was started by the AC mode and stopped by the DC mode of the ultrasonic motor. The results of five travels for each position from 0.1mm to 15mm are listed in Table 2. Accumulated errors are clearly seen due to the alignment error of the grating to the motion axis. Standard deviations are from 7nm to 17nm.

Some possible error sources were found as follows:

1. The straightness polish of the guideway contact was not satisfactory. The induced variable friction forces yielded unsteady motion, which caused the noisy signals of the LDGI output.
2. The quality of the holographic gratings is also of major concern. The uniformity of the grating pitch and the depth will influence the diffraction effect and accordingly alter the DC drift and amplitude of the sinusoidal signals. In addition, improper cutting of the glass gratings creates scratches.
3. The stability of ambient temperature and the ground vibration are also factors which impact on the system

accuracy.

4. Electrical noise from circuit is an error factor. It yielded Interpolation error. In this system, the peak to peak voltage is about 3V and the noise is about 50mV. After calculated to displacement, the interpolation error is about 3.1nm.

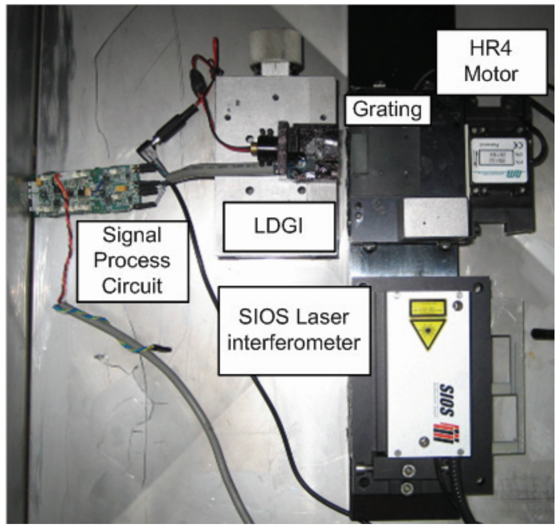

Fig.6. The experimental setup.

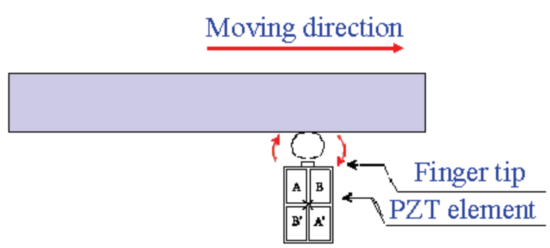

Fig.7. Motion principle of the ultrasonic motor

Table.2. Positioning error tests (nm).

Position (mm)	0.1	1	5	10	15
Error 1	-7	420	1570	3080	4623
Error 2	-16	425	1553	3043	4629
Error 3	13	414	1589	3078	4591
Error4	-3	409	1581	3085	4607
Error5	7	424	1561	3061	4601
$\overline{\text{Error}}$	-1.2	418.4	1570.8	3069.4	4610.2
Standard deviation	11.5	6.8	14.6	17.3	15.7

4. CONCLUSION

We have demonstrated the developed laser diffraction encoder which adopts the special design of optical path to enhance alignment tolerances between optical head and linear grating. It has some advantages, such as compact size, high stability and high resolution. In addition, the signal process circuit effectively decreases the DC shift error, the electronic gain error and the phase orthogonal error of two sinusoidal output signals. The result demonstrated the standard deviation is below 17nm for a 15mm long travel in normal laboratory environment. Finally, we discussed some possible error sources. In the future, we will focus on these errors sources and continue to improve it.

REFERENCES

[1] S. Ishii, T. Nishimura, K. Ishizuka and M. Tsukiji, Optical type encoder including diffraction grating for producing interference fringes that are processed to measure displacement, U.S. Patent 1990, No. 4,912,320.

[2] R. Sawada, E. Higurashi, T. Ito, O. Ohguchi and M. Tsubamoto, Monolithic-integrated microlaser encoder, Appl. Opt. 1999, 38(33), 6866-6872.

[3] W.W. Chiang, and C.K. Lee, Wavefront reconstruction optics for use in disk drive position measurement system, U.S. Patent 1995, No. 5,442,172.

[4] C.C. Wu, C.K. Lee, S.S. Lu, W.J. Chen, C.S. Yang, and C.T.Hsieh, Diffractive laser optical encoder with high tolerance to high-speed mechanical runout, Journal of Chinese Institute of Engineers 2001, 24(4), 419-429.

[5] T. Nishimura, Y. Kubota, S. Ishii, S. Ishizuka, and M. Tsukiji, Encoder incorporating a displaceable diffraction grating, U.S. Patent 1991, No.5,038,032.

[6] X.M. Chen, K.C. Fan, Fabrication of compact laser diffraction encoder system with high alignment tolerance, Master Thesis 1995, National Taiwan University.

[7] P. L. M. Heydemann, Determination and correction of quadrature correction of fringe measurement errors in interferometers, Appl. Opt. 1981, 20, 3382.

[8] K.C. Fan, Y.T. Fei, X.F. Yu, Y.J. Chen, W.L. Wang, F. Chen and Y.S. Liu, Development of a low cost Micro-CMM for 3D Micro/nano Measurements, Measurement Science & Technology 2006, 17, 524-532.