XVI IMEKO World Congress
Measurement - Supports Science - Improves Technology - Protects Environment ... and Provides Employment - Now and in the Future
Vienna, AUSTRIA, 2000, September 25-28

APPLICATION OF FOCUSED LASER BEAM IN LINEAR ENCODER

M. Dobosz
Institute of Metrology and Measuring Systems. Faculty of Mechatronics
Warsaw University of Technology
Chodkiewicza 8 St. 02-525 Warsaw, Poland

Abstract: The idea of high resolution (0,01 µm) displacement encoder with laser diode light beam focused on the scale surface is presented. Due to application of the focused laser beam the acceptable tilts of the encoder head relative to the grating in the prototype device reach about of 0,5 arc degree in all directions and the tolerance of the distance between head and the grating is equal to about 0.1 mm. A new simple reference point detection method that use a scale grating edge as an reference point has been proposed. This technique allows significant reduction of nonlinearity errors of the measuring system. Nonlinearity of the prototype device does not exceed 0,1 µm in 48 mm measuring range.

Keywords: displacement measurement; interferometer; laser diode; diffraction grating; focused light

1 INTRODUCTION

High resolution and high accuracy compact linear or angular displacement transducers (encoders) are widely used in various industrial fields. The systems developed in last ten years use the laser diode semi-coherent light to create interference fringes from the diffracted light.

One of the most difficult design task in high resolution encoders is to make the system insensitive to disturbing shifts and tilts of the scale relative to the detector head. These additional motions always exist due to the inaccuracy of the grating guide and imperfect alignment. To solve above problems we suggested to focus the light on the grating surface. The additional advantage of this proposition is that the same light beam may be used for reference point detection. In the previous paper [1] we presented theoretical analysis and feasybilities of a grating interferometer in which the light is focused on the grating surface. In this paper we present shortly general description of the grating interferometer, design of the prototype device and its metrological feasibilities.

2 PRINCIPLE OF THE INTERFEROMETER

The basic principle of the interferometer is shown in Fig. 1. A laser diode (LD) beam is focused by lens L on the surface of the grating G. The resulting first diffraction orders are directed to a beamsplitting surface BS by means two reflecting surfaces M1 and M21. Mirrors M1, M2 and beamsplitting surface BS are made as side surfaces of double prism DP. The ± first – order diffracted beams interfere in the planes of photodetectors P1 and P2. As the scale G is moved along the axis lying in the plane of the grating and perpendicular to the grating lines, the light frequency in the ± first diffraction orders changes according to the Doppler law.

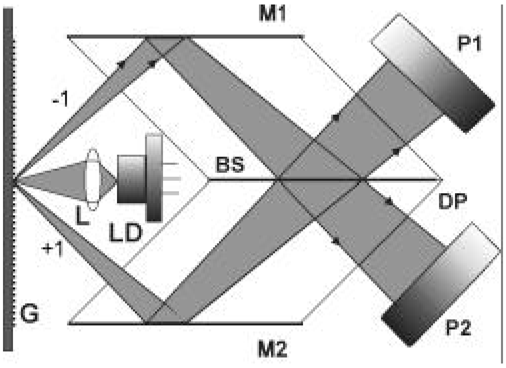

Figure 1. Basic principle of the interferometer

As a result a signal with two sinewave periods per grating pith is obtained from the photodetector. So, if a counting fringe technique is used the displacement of the grating will be measured with high resolution.

3 DESIGN OF THE PROTOTYPE DEVICE

The prototype transducer design is shown in Fig. 2. Laser diode LD emitting 670 nm wavelength is applied (SANYO ULD) as a source of light. Set of the lenses L creates a laser beam waist (about of 70 µm in width) on the grating G surface. Right-angle prism RP, mirrors M1 and M2 direct light beam onto the grating G. The resulting first diffraction order beams are forced to interfere in the plane of photodetector P2 and P1 (invisible in Fig. 2) by means of beamsplitting prism BSP. Beam splitting surface is made on one of the component prisms of the double prism BSP. Shifts and rotations of elements L, RP, M1, M2 allow adjustment of the system. Arrows shown in the figure indicate the degrees of freedom for each element adjustment. In our transducer we have applied the reflecting phase sinusoidal grating with a pith equal to 1 µm.

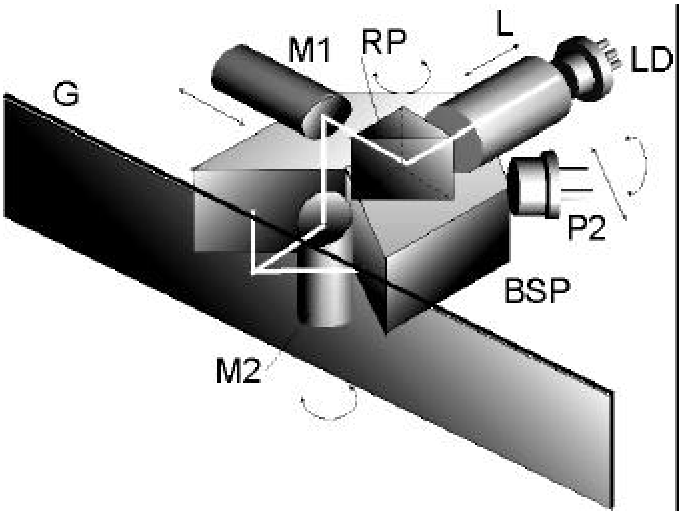

Figure 2. Design of the prototype encoder

Photocurrents generated by photodiodes are converted into the voltages to form two output signals being in quadrature. Both output voltages are next sampled and digitized by fast A/D converters.. Digital representation of actual values of both signals is accepted as an argument of the interpolation function which is stored - as a matrix - in read-only memory in accordance with multiplication factor of interpolation. The values of interpolation function, that appears on the data bus, are read by logical circuit, which utilizes them to generate DIRECTION and PULS signals for reversible counter, which provides indication on the display. In our experiments we have fixed the detecting head to the ball bearing guided carriage.

4 A NEW DETECTION METHOD FOR THE REFERENCE POSITION

We applied a new simple reference point detection method that use a scale grating edge as an reference point. One of the possible ways of realization of this method is digital signal amplitude extraction. In every set of incremental transducers two following output signals are generated

$$U_1 = A\sin(wx) \tag{1}$$

$$U_2 = A\cos(wx) \tag{2}$$

where A is an amplitude of the signal, x is the grating position. By digital signal analyzing we obtain the following output signal

$$U = \sqrt{U_1^2 + U_2^2} = 2A \tag{3}$$

Amplitude A, thus the voltage U drops to zero at the boundary of the grating. Signal U compared with the voltage threshold gives information about grating edge position.

In the prototype device we used the edge of the substrate as the grating edge. Because of the edge diffraction effects and photoresist meniscus the zone between the grating and the end of the substrate was equal to about 200 µm. So we didn't expect very high repeatability of the reference point detection. But, since we used this edge only for errors compensation the obtained accuracy of reference point detection was satisfied.

For the purpose of testing the repeatability of such a reference point detection a carriage with the encoder was moved so that the laser beam waist went across the edge of the grating. The software of the encoder interface zeroed the encoder counter readings at this point. Next the reference interferometer released reading of the encoder in selected position of the measuring range. The spread of the obtained results in repeatable measurements were caused mainly by reference position detection inaccuracy. The obtained repeatability (±3s) was equal to about 3 µm.

We have also made separate tests in which we have checked the repeatability of the edge detection when the grating edge zone was reduced to several micrometers (the part of the grating was removed from the substrate). In this case we have obtained random error (±3s) of edge detection equal to about 0.3 µm.

5 ACCEPTABLE DISTURBING MOVEMENTS OF THE GRATING

In the paper [1] we confirmed that the laser beam focused on the grating surfaces reduces significantly the system sensitivity to disturbing shift and tilts of the grating relative to the detection head. To evaluate the sensitivity of the device to the disturbing tilts and shifts of the detection head relative to the grating, we have controlled the head angular and linear displacements and measured the resulting change in amplitude and phase of the output signals by means of digital oscilloscope. Since applied interpolating electronics theoretically is insensitive to the amplitude of the output signal variations of the detecting head we have assumed that the acceptable decrease of the signal amplitude is about 10%. Summary of this test is shown in the table 1.

Table 1. Acceptable disturbing movements of the reading head relative to the grating

Component of the disturbing movement	Value of the displacement effecting in 10% change of signal amplitude	Change of the phase shift between output signals in the given range of displacement
Turn of the grating around its lines.	±18 arcmin	not observed in this range
Rotation of the grating in its own plane.	±15 arcmin	5 degree
Rotation of the grating around the displacement axis.	±13 arcmin	not observed in this range
Change of the distance between detecting head and the grating	± 60 µm	10 degree

We didn't expect any influence of the rotation of the grating around the displacement axis on the output signals, but when testing the prototype device we obtained quite strong influence of this disturbing effect on the signal amplitude. This disagreement is simply caused by too small light spot in the photodetector plane (in the direction normal to the interferometer plane) in comparison with the photodetector size. In this case when the grating is tilted the interference zone moves in the photodetector plane reducing photodetector signal level.

6 INACCURACY OF THE DISPLACEMENT TRANSDUCER

Applied interpolator unit make it possible to choose interpolation factor from 1 to 100. It results in theoretical encoder resolution from about of 0.1 µm to 0.005 µm. Since we couldn't verify the accuracy of the encoder in nanometer range we have chosen 0.01 µm resolution for our tests. For the purpose of testing repeatability of the device with the above resolution we applied pizoelectric positioner having expansion coefficient equal to 15 µm/10V (Phisical Instrumente, P-821.10).

The applied scale gave approximately 50 mm measuring range. To test nonlinearity of the encoder in full measuring length we applied laser interferometer with a 0.01 µm resolution (Carl Zeiss Jena - ZLM 100).

6.1 Encoder repeatability

To test the encoder repeatability we applied very accurate (2 nm position inaccuracy) piezoelectric translator. The encoder head was forced by the translator to vibrate (we applied small vibration frequency about of 1 Hz) relative to the grating. Consecutive encoder readings were compared with positions measured by the piezo-translator and stored in computer memory to make possible statistical analysis of the spread of the results. We changed the amplitude of vibration to obtain different velocity of carriage movement during position reading. Applying displacement velocities equal to 5 µm/s and 50 µm/s we obtained the short term repeatability (from 50 elements samples) of the transducer equal from 0.02 µm to 0.03 µm (range). This spread is fully explained by the digitization error of the encoder.

We have also checked the repeatability of the prototype device in dynamic measurement with a velocity of about 500 µm/s. However in this test we applied a reference HE-Ne laser interferometer characterized by relatively small resolution of 0.01 µm. The reference interferometer was used to sample the encoder interface unit readings with a constant step of the carriage movement. Pulses created by the reference interferometer triggered the encoder readings and stored them in the personal computer PC memory.

The repeatability of the device was estimated based on more than 50 element samples taken in selected positions of the measuring range. The obtained repeatability in this test was equal to 0.07 µm. The contributing component of this spread are following;

- digitization error of the encoder - equal to ± 0.01 µm.,
- digitization error of the reference interferometer - equal to ± 0.01µm.,
- reference interferometer instability - approaching 0.03 µm during measurements,
- mechanical instability of the measuring system .

6.2 Encoder nonlinearity

The reference point was used for the purpose of nonlinearity errors compensation in the full measuring range, i.e., 48 mm. The reference interferometer was first used for nonlinearity errors evaluation. The interferometer sampled the encoder interface unit readings with a constant, 32 µm encoder movement step. This value results from using the reference interferometer binary counter to generate sample signal. Pulses created by the reference interferometer released the encoder readings and stored them one by one in the computer memory. Next the regression analysis of the obtained data matrix was used to obtain the residuals of the results from the linear regression model. This residuals represent nonlinearity errors of the system. In the experimental set-up the nonlinearity errors were generated by the carriage guidance imprecision because the axis of reference interferometer displacement measurements was shifted laterally relative to the axis of the encoder displacement measurement (Abbe principle was not fulfilled exactly).

The vector of residuals (nonlinearity errors) was next input to the encoder interface software for automatic error compensation. The error compensation consists on subtracting the residual value from the obtained results (before compensation). The value of subtracted residual remain constant in every sampling interval (in this case equal to 32 µm). Finally the nonlinearity of the measuring system was evaluated again, applying numerical error compensation. The exemplary result of such a test is shown in Fig. 3. Points where the reference interferometer released readings of the encoder, are marked on the abscissa. The nonlinearity errors (i.e. residuals from the regression) are marked on the ordinate. Points denoted by ○ refer to the residuals before numerical compensation. Points marked by + refer to the data obtained in the second cycle after numerical error compensation. Since we didn't observe any return error of the system, only the data obtained in one-directional movement are presented. The maximum value of nonlinearity error observed in Fig. 3 in full measuring range (48 mm) before numerical compensation of the errors (caused by a straightness error of the grating slideway) reaches about ± 0.2 µm. After correction the nonlinearity error of the encoder measuring system doesn't exceed about ± 0.05 µm. In fact the real value of the nonlinearity after correction is lower because it is masked by the random spread of the results caused by digitization errors of the reference interferometer, and encoder (both ± 0.01 µm) and random part of the guidance inaccuracy.

In our research we assumed that the nonlinearity is a long-period error. That is why we have applied numerical error compensation of 32 µm steps, and 3 µm inaccuracy of the reference point detection. But if necessary, it is possible to improve the results by applying smaller compensation step (it requires only more memory for the residuals vector storage) and greater reference point repeatability (it can be improved 10 times by cutting the grating at the edge).

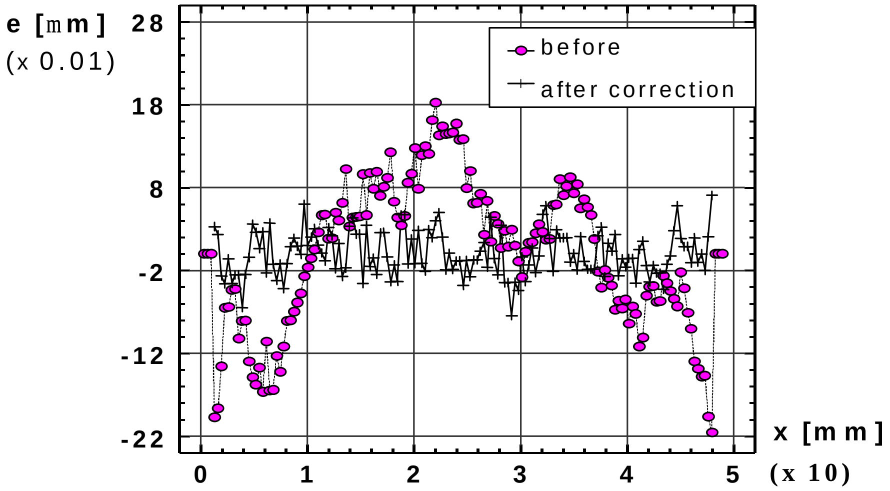

Figure 3. The exemplary result of encoder measuring system’s nonlinearity test

7 COCNCLUSIONS

The results of research presented herewith shows advantages of applying focused laser beam on the grating surface in high resolution displacement encoder. First of all the proposed optical system is extremely insensitive to disturbing shifts and tilts of the scale. The acceptable tilts of the encoder detection head relative to the grating in the prototype device reached about of 0.5 arcdegree in all directions. The tolerance of the distance between detection head and the grating is about 0.1 mm.

The second, advantage of applying laser beam focused on the scale surface, confirmed by our research is that the same light beam can be used both for displacement measurement and for reference point detection. This feature makes possible the systematic error correction with a very simple encoder design. We have shown that the nonlinearity errors generated, for example by the slideway nonlinearity (when the offset between measurement axis and length master axis exist) can be reduced to the level of 0.1 µm in approximately 50 mm measuring range.

We have shown very simple design of the prototype encoder allowing a low price of such a systems.

REFERENCES

[1] M. Dobosz „Application of focused laser beam in a grating interferometer for high resolution displacement measurement” *Optical Engineering* **38** (6) (1999) 958-967.

[2] M. Dobosz „High resolution laser linear encoder with numerical error compensation” *Optical Engineering* **38** (6) (1999) 968-973.

AUTHOR: Ass. Prof. Dr. Marek DOBOSZ, Institute of Metrology and Measuring Systems, Faculty of Mechatronics, Warsaw University of Technology. Chodkiewicza 8 St. 02-525 Warsaw, Poland
Phone: (4822) 660-8347, Fax: (4822) 49-03-95, E-mail: dobosz@mech.pw.edu.pl