1D high precision interferometer-controlled comparator

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ABSTRACT: A measurement stage for characterization and calibration of a new precision incremental encoder for measuring legths up to 1 mm has been developed. An exposed linear encoder with a phase grating applied to a carrier of glass ceramics Zerodur has been used as a reference system. The grating period of 512 nm has resulted in a measuring step of 0.125 nm (after interpolation). It has been proven that the system displays better reproducibility and lower sensitivity to the ambient conditions variations compared with a laser interferometer. The measurement facility developed enables us also to investigate and evaluate the contribution of both the geometrical errors and thermal disturbances on the grating, encoder's metrological properties.

1. Introduction

The access and availability of metrological tools that have the ability to measure with nanoscale resolution over large areas are essential for product development of nano- and microtechnologies. Advanced position measurement and control tools are to be regarded as primary technology drivers in such industries as semiconductor fabrication, high density mass data storage systems, high precision machine tools, MEMS and other. Phase grating sensing techniques are well positioned to meet these challenges of miniaturization in manufacturing technologies [1].

The paper describes the work at PTB in high-precision length metrology aimed at development of low uncertainty measurement facilities in 1D metrology as well as precision advanced positioning mechanisms. The research has been carried out within the framework of DFG (Deutche Forschungs Gemeinschaft) supported field of research No. 516 that aims at developing technologies for design and manufacturing of active microsystems. To demonstrate these new technologies a closed-loop positioning system with miniaturized linear actuator and integrated incremental measurement system is required.

A precision single axis comparator has been designed, constructed and tested, and series of measurements were conducted to evaluate the system performances. It will also used as a measurement setup to carry out reproducible measurements and testing of linear encoders with different parameters and to determine which effects and modifications, as for example alignment of the scanning head or variation of the ambient conditions, influence the measurement system.

2. Experimental Setup

A precision single axis displacement measuring system - 1D interferometer-controlled comparator - was designed and built up to carry out experiments. It allows to measure and calibrate linear encoders within the displacement range of 1 mm. The comparator basically consists of the piezo-driving system, heterodyne laser interferometer, exposed interferential linear encoder and environmental condition controller. Position information from the encoder and stage displacement measuring interferometer can be evaluated independently.

The whole system is maintained by two PC. The central computer handles the user interface, the control of the measurement process, measurement data acquisition and evaluation. The second PC runs independently from the data acquisition over a long period of time and serves as environmental condition control unit. Fig. 1 shows the outline of the measurement setup.

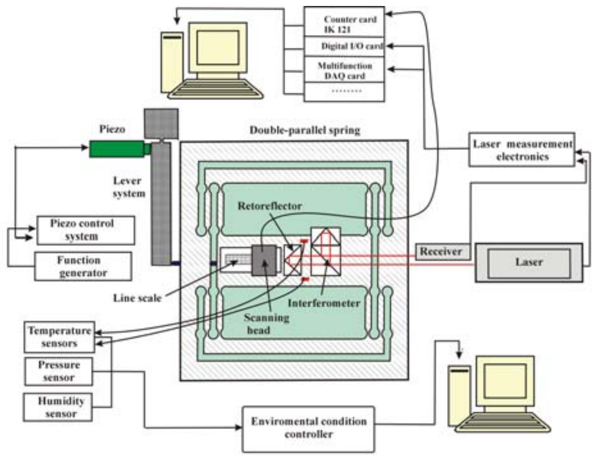

Fig. 1 Principal setup of the measurement system

A double-parallel-spring mechanism manufactured from a plate of high-quality steel is used as a precision translation stage.

The spring elements consist of eight bars. The diminution of their cross-section causes them to act as elastic pivots. Four of these spring elements are connected to the external fixed frame, the others support the central bar. The alignment deviation of this double parallel spring is less than $5 \cdot 10^{-8}$ rad.

The encoder grating and the target retroreflector of the laser interferometer are mounted on the central bar of the spring. Mountings for the line scale of the encoder and a triple retroreflector are fixed on the central bar of the spring. The displacement of the central bar is provided by a piezo translator with a nominal increment (step size) of 120 µm, which is multiplied up to 1 mm with the help of a lever system. The transmission ratio is 1:20; the displacement is reduced because of limited stiffness of the piezo.

The whole setup is placed on a vibration-insulated laboratory table.

3. Processing Electronics

Measuring electronics handles all the system control and data processing tasks.

The electronics for a heterodyne displacement measuring interferometer signals processing is based on the Zygo AXIOM Measurement Board. Its circuitry converts the optical phase information of the interferometer measurement and reference signals to a 32 bit (or 36 bit) 2's complement position value. The processing electronics provides means to acquire motion data and system status from the interferometer system to a user program running on a personal computer (PC) with a position resolution $\lambda/512$ (1.25 nm). The measurement data are calculated in real time at the rate of the measurement signal frequency 7-13 MHz.

The encoder with produced sinusoidal scanning signals is connected to the IK 121 PC-board from HEIDENHAIN. The IK 121 counter card subdivides the periods of the sinusoidal encoder signals up to 1024-fold, which yields a resolution of 0,125 nm. The result of interpolation is sent as a code value to the PC where it is processed.

The piezo translator is driven by analog voltage signal from 0 to 10 V, which can be generated by D/A converter card or by function generator; the latter allows higher measurement data acquisition rates.

Analog inputs with 16 bit resolution are available for read-out of the inductive sensors. All measurement systems are triggered by a synchronous hardware trigger, generated by the industrial PC. Data acquisition rates amount to 100 Hz.

All electronic components are installed in a special 19“ housing.

4. Reference Measurement System

Prior to investigate and calibrate the new incremental encoder that is being developed at the Laser Zentrum Hannover (LZH), the accuracy and reproducibility of the experimental stage were tested by comparing the properties of laser interferometer and reference interferometric grating encoder. Heidenhain LIP 382 with Zerodur scale was applied as reference length measurement system. Figure 2 shows the configuration of the reference encoder [2]. The scale of the glass ceramic Zerodur carries on its upper side a phase grating of chromium lines with a grating period of 512 nm. The scanning head consists essentially of a light source, an index grating, a cube-corner prism, and three photodetectors.

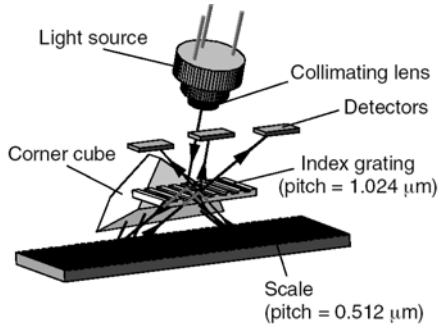

Fig.2 Schematic diagram of linear encoder

The collimated light beam, which is perpendicular to the direction of measurement but oblique in the line direction, falls on the index grating with a grating period of 1024 nm, where it is diffracted into three orders. The zero order is hidden, and only the ±1st orders strike the scale, where they are diffracted in Littrow arrangement and, inclined in the line direction, are reflected into a cube-corner prism that reflects both beams in parallel offset onto the scale. There they are diffracted once again, reflected, and finally interfere on the index grating at a certain distance from the incident beam. Photodetectors convert the 120°-phase shifted optical signals into electrical output signals which are transformed into quadrature signals. The two-fold diffraction gives a signal period of 1/4 of the scale pitch, i.e., 128 nm and an electronic interpolation by a factor of 1024 leads to a measuring step of 0.125 nm.

5. Experiments

The comparison of two high-precision length measurement systems has been carried out in air-conditioned measurement room with a room temperature of 20 ^{o}C at PTB.

Zygo AXIOM 2/20 heterodyne laser measurement system was selected for laser interferometer, and it can detect motion as small as 1.25 nm. The laser measurement system is comprised of four main components: laser head, interferometer, receiver and measurement electronics. The He-Ne laser head with the help of acousto-optic frequency shifter generates light (λ=632.991528 nm) of two different frequencies, f_1 and f_2, with orthogonal polarization and frequency shift of 20 MHz [4].

Interpolation nonlinearities of 5 nm were observed during previous measurements of this laser interferometer [5]. Long-term stability of the laser interferometer was mainly influenced by temperature and refractive index. The refractive index of air was compensated with Edlen formula. Comparison of measurement fluctuation of both systems in air-conditioned laboratory is presented in Fig. 3.

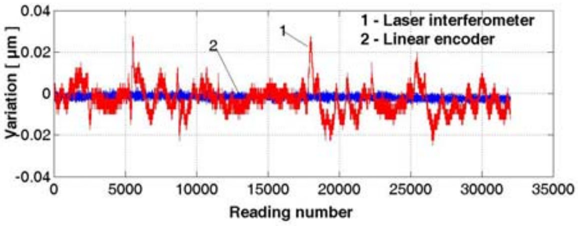

Fig.3 Stability of laser interferometer and reference encoder in static mode

Both measurement systems were synchronously read out in static mode. The complete measurement lasted 14 s. As it can be seen from the data presented in Fig. 3 actually in comparatively good ambient conditions the interferometer reveals clearly higher variances than the incremental encoder.

The dynamic mode of operation was called to provide by applying the sinusoidal input of 0.3 Hz and 10 V magnitudes to the piezo translator. This resulted in the displacement of the double spring mechanism on 900 µm. The discrepancy between readings of reference encoder and laser interferometer over 900 µm measurement length is of the same order as variations of the laser interferometer measured in static mode, see Fig. 4.

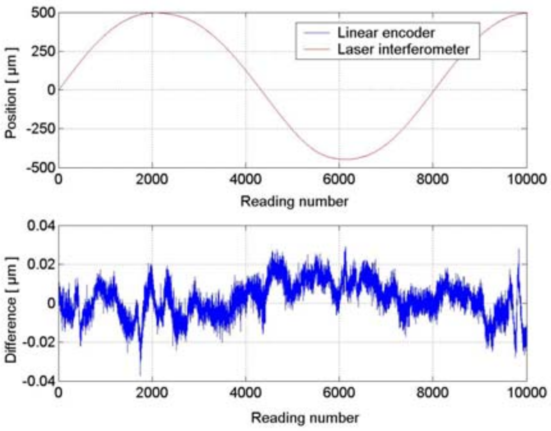

Fig.4 Length measurement variations (discrepancy between readings of linear encoder and laser interferometer) in dynamic mode

Repeated measurements on different positions of the line scale displayed quite similar results. Temperature measurement system due to its data acquisition time in the range of 30 s and remoteness of the laser beam sensor is not able to compensate these variations. Therefore correction of measured value of the reference system for further investigations is not needful [6].

The measuring setup was tested with the help of an incremental encoder with signal period of 2 µm. Series of measurements over 200 µm length are presented in Fig.5. If smaller range of 20 µm is taken up, the interpolation nonlinearities of 20 nm with the period of 2 µm are clearly recognised, see Fig. 5c. To identify frequency components of the signal presented in Fig. 5b FFT (Fast Fourier Transform) was applied, see Fig. 5d. Due to very small signal period of the reference system its interpolation variations are not seen here. Thus the experimental setup for estimation of interpolation variations in the claimed accuracy range could be applied.

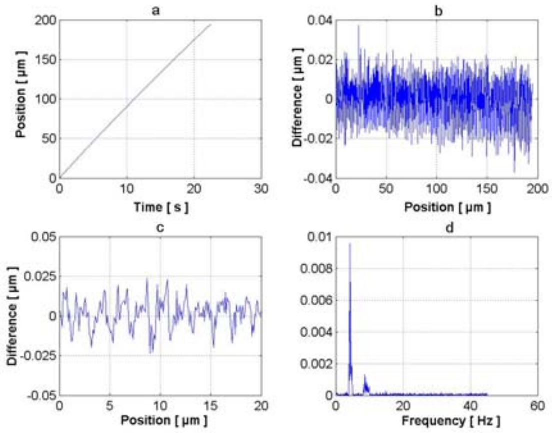

Fig.5 Comparison of two linear encoders: a) position values measured simultaneously with both linear encoders vs time, b) difference between measured values, c) difference between position values within a range of 20 µm, d) Fourier transform of the signal shown in 5b.

To test the performance of the measured encoder under variation of its geometrical parameters special brackets were manufactured for the mounting of the piezo translator that was designed to tilt the scanning head of the encoder within one arc minute. The scanning head was mounted on the L-form bracket with a nick on the lower part. In this way the lower part of the mounting is able to act as a pivot and can be tilted together with the scanning head by the piezo translator. The deflection was measured with an inductive sensor.

The influence of geometrical errors on performance of the measurement system and its nonlinearities can be determined by arrangement of tilting of the scanning head. The results of the experiment conducted are depicted in Fig. 6.

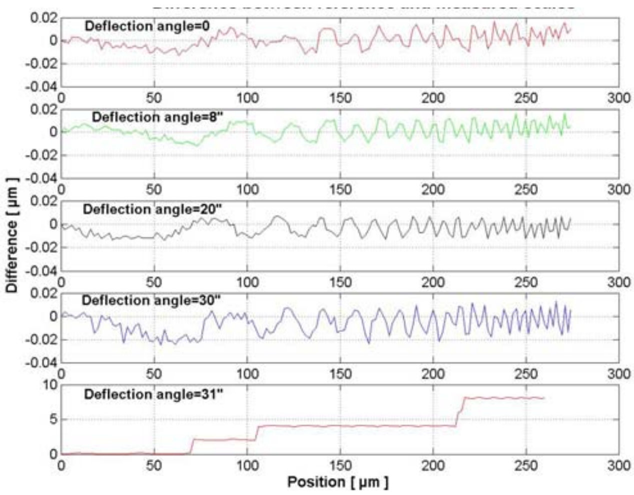

Fig.6 Difference between readings of reference and measured linear encoders

With the help of measurement setup can be ascertained that investigated measurement system operates reliable at velocities up to 26,7 mm/s. Motions up to 1 mm with frequencies of f=10 Hz generated by function generator were exercised. Whenever the measurement system is not able to count fast enough, the difference between both measurement systems from period to period is getting larger. Owing to the experiments carried out it has been concluded that the frequency limit for the test system is 11 Hz.

6. Conclusions

A measuring device - precision 1D comparator - for investigation of length measurement system within small measurement range was developed. An incremenal linear encoder with the grating period of 512 nm and a line scale made of Zerodur was used as reference system. Experiments conducted at PTB have shown that users can expect fewer fluctuations of the position display from scale encoders than from laser interferometers. It has been shown that series of measurements with reproducibility smaller than 30 nm can be carried out using a small incremental encoder with the grating period of 2 µm. Using multi-channel temperature and control system the impact of thermal interferences for the test item can be evaluated. Furthermore with the help of tilt system for the scanning head of the measurement device series of measurements with varying adjustment of the scanning head relatively to the line scale can be accomplished.

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