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Investigation of calibration facilities of precision line scales

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1. Introduction

The measurement of length is one of the problems with which science and industry are confronted most frequently. To meet the highest requirements, for example in the measurement of semiconductor structures, high density mass data storage systems, high precision machine tools, Micro Electro-Mechanical Systems (MEMS) and other, lengths must be known with uncertainties of the nanometer range.

Dimensional metrology requires that a great number of length divisions must be available in the range from 0 to about 1 meter, whose lengths are known with high accuracy, i.e. they must be traceable to the unit of length, the meter, and its multiples and fractions [1].

Optical and optically performed measurements have become essential as modern metrology thanks to their higher accuracy and the enormous expansion of the optical industry. The use of traditional length standards, line scales and encoder gratings is becoming more common. Improvements and application of microscopy, modern lithography, laser interferometry increase the required accuracy level and the efficiency of line standards calibration. Currently static line detection systems mostly used in metrology institutes and calibration laboratories worldwide are to be replaced by the systems using dynamic calibration methods and the newest technical achievements.

The paper describes the work in high-precision length metrology aimed at the development of low uncertainty measurements in 1D metrology as well as precision advanced positioning mechanisms.

A precision 1D comparator has been designed, constructed and tested, and series of measurements were conducted to evaluate the system. The setup is intended for characterisation and calibration of a new precision linear encoders and line scales. It will be 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 influence the measurement system. The required uncertainty for the evaluation of the measurement setup reaches 30 nm.

Several measurements using a microscope with charge-coupled device (CCD) performed to investigate dynamical capabilities of the system are presented in this paper too.

2. Experimental setup

A precision single axis displacement measuring system - 1D interferometer-controlled comparator - was designed and built up at German National Metrology Institute (PTB) to carry out experiments. It allows to measure and to 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 personal computers (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.

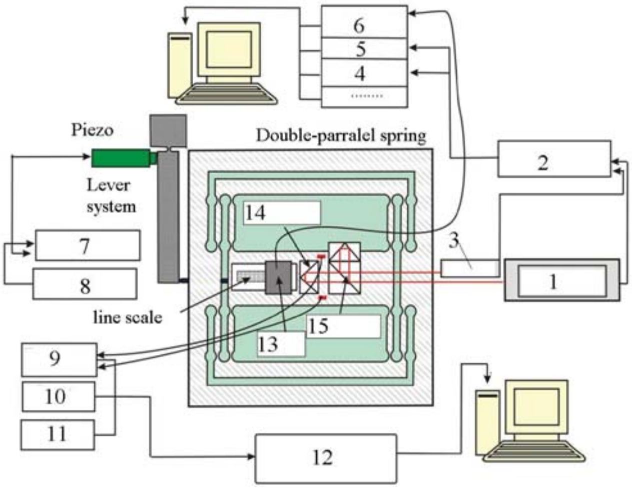

Fig. 1 Principal setup of the measurement system: *1* - He-Ne laser, *2* - laser measurement electronics, *3* - receiver, *4* - multifunction data acquisition (DAQ) card, *5* - digital I/O card, *6* - counter card IK 121, *7* - piezo control system, *8* - function generator, *9* - temperature sensors, *10* - pressure sensor, *11* - humidity sensor, *12* - enviromental condition controller, *13* - scanning head, *14* - refefelector, *15* - interferometer

A fine positioning system has been designed for nanometer accuracy measurements. 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.

A bridge, bolted together out of three massive steel parts, is arranged within the frame of the double spring. The bridge provides a support for a beam splitter that is coupled with a reference reflector of the laser interferometre. The scanning head of the encoder is mounted on a L-form bracket that can be aligned to the translation axis.

The whole setup is placed on a massive vibration isolated laboratory table.

3. Processing electronics

An industrial PC handles all the system control and data processing tasks. All electronic components are installed in a special housing.

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

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.

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. One of two frequencies, f_1, is optically separated in the beamsplitter and directed to the target reflector. The second frequency, f_2, is separated and sent to a fixed reflector and then rejoins f_1 at the interferometer to produce an interference signal. As the target reflector moves, the returning beam frequency will be Doppler-shifted up or down by Δf_1 depending on the direction of motion. The receiver changes f_2 and $f_1 \pm \Delta f_1$ to an electrical signal. Electrical measurement and reference signals are sent to the Measurement Board AXIOM 2/20. Here phase detector calculates phase difference between reference signal and measurement signal. Accumulator adds up the phase differences and outputs measurement data in 32-bit binary words.

The laser interferometer output signal goes to a photo receiver in the measurement board - a register based Industry Standard Architecture (ISA) bus slave card used with Zygo motion measuring interferometers. The receiver produces an electrical measurement signal corresponding to the optical signal. 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 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 Zygo ISA bus interface provides a capability to transfer data using 16-bit word lengths. Typically all motion registers are 32 bits in length. However, the position data resides in 36-bit registers within the electronics. These registers can be accessed in three 16-bit transfers. In addition, these registers can be configured to output any 32 bits of the 36 bits when the register is read with two 16-bit transfers [2].

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.

4. Temperature measuring system

Temperature impacts are very often the accuracy limiting factor in dimensional metrology. Temperature, barometric pressure and humidity influence the refractive index of air and, thus, the wavelength of light; temperature also affects the length of the scale being measured.

Interferometer air path temperature and scale temperature have been measured with a multi-channel temperature measurement system developed at PTB for the comparison of laser interferometers and interferometric grating scales [3].

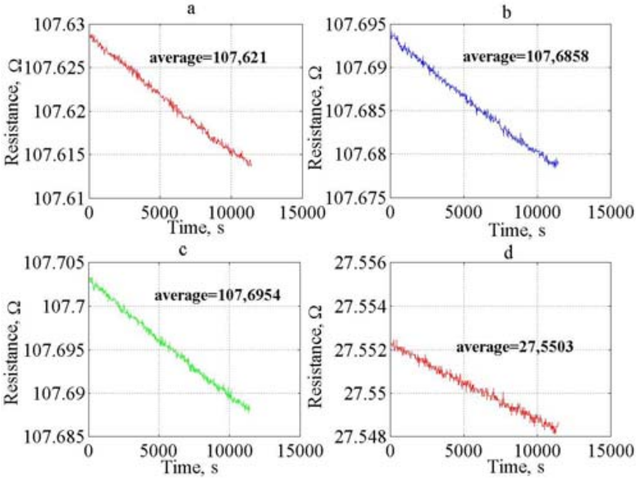

Fig. 2 Stability of Pt 100 sensors and reference resistor during calibration at temperature 19^{o}C: *a, b, c* - stability of three different Pt 100 sensors; *d* - stability of the reference sensor Pt 25

The electronic system is able to function with different types of temperature sensors, e.g. thermistors, thermocouples, Pt 25 and Pt 100 platinum resistance thermometers. The Pt 100 resistance thermometers were chosen for experiment purposes because of their high stability; the thermocouples, due to their sensitivity characteristic curve shape, are not suitable for temperature ranges of several Kelvin.

A temperature range of 19°C to 22°C was used during the length measurements and a range of 0°C to 40°C was used for testing at the temperature fix points. The resistance and hence the temperature value of Pt 100 sensor is computed by interpolation relative to the reference resistors. The stability of Pt 100 sensors during their calibration process is shown in Fig.: 2 and 3. Influences from thermo voltages at the connectors and from electronic multiplexers are compensated by the application of a self calibration procedure.

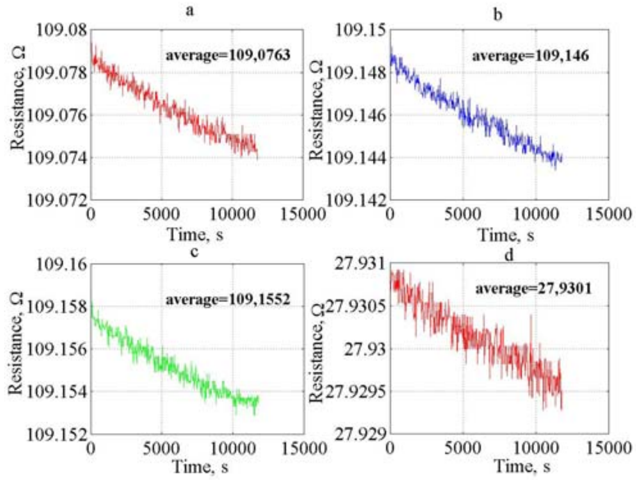

Fig. 3 Stability of Pt100 sensors and reference resistor during calibration at temperature 22 °C: *a, b, c* - stability of three different Pt 100 sensors; *d* - stability of the reference sensor Pt 25

The whole sequence of a temperature measurement takes approximately 0.5 s for one temperature sensor. Each multiplexer card has 16 connection inputs. Two of the 16 connections are used for very stable and well known reference resistors. Additionally Pt 25 sensor can be connected as reference for calibration of the temperature measurement unit. The total number of sensors that the system can handle amounts to 100.

Each temperature measurement is done by a sequence of three resistance measurements:

1. reference resistor representing a well specified temperature point at the lower end of the measuring range;
2. Pt 100 resistance of the temperature to be determined;
3. reference resistor representing a well specified temperature point at the upper end of the measuring range.

Necessary calibration of Pt 100 sensors has been carried out in copper block with the holes for the sensors. The copper block hangs within an isolated oil bath. The temperature of the bath can be changed due to water coils outside of the isolation. A very large time constant due to the mass of the block and the isolation is responsible for a good temperature stability. The Pt 100 resistance thermometers have shown nonlinearities up to 25 mK for a temperature of 17°C, when calibrated at triple point of water (0.01°C) and the gallium melting point (29.7646°C).

As reference for the calibrations serves a Pt 25 resistance thermometer which is attached to temperature fixed points of International Temperature Scale (ITS 90), the triple point of water and the melting point of gallium. Measurement uncertainty of 5 mK for Pt 100 sensors over recalibration period of one year is achievable [4].

Temperature measurement system of the stage components has four analog outputs. Four heat sources with the aid of an amplifier and thermal resistors can be used for reproducible series of measurements. That would enable simulation of thermal dissipation loss of linear motor whose operating temperature must be controlled as well as the influence of temperature distributions over scanning head would be of interest too.

To determine refractive index of air a capacitive pressure measurement system (Setra Systems, Inc.) was added to the temperature measurement unit.

5. Measurement procedures

For high precision measurements of line scales two main modes of calibration are basically applied: static and dynamic calibration. Dynamic calibration mode offers taking advantages of precision line scale calibration in terms of speed, accuracy and efficiency. It also allows the construction simplification, because high precision settling of the moving scale or microscope is not needed, and the measurement process is less influenced by environmental conditions.

Currently static line detection systems are mostly used in metrology institutes and calibration laboratories worldwide. The static method is potentially more accurate but somewhat slow, whereas the dynamic method encounters difficulties with speed fluctuations, time delays and noise especially during the graduation line detection. Other error-related problems specific to length measurements are caused by angular deviations of the microscope or distance variations between scanning system and the scale.

Both systems employ a computer that controls the measurement process by a set of input instructions. The distance measurement can be carried out automatically between multiple graduation lines, with line separation from 1 mm to slightly over 1000 mm. The number of runs can be set individually. In a single run the microscope carriage is moving in only one direction.

In the static mode the line scale is calibrated by moving a carriage of a photoelectrical microscope (or the line scale itself) to a distance that is equal to the interval between two graduation lines. When the carriage stops and the line gets into the field of view of the photoelectric microscope the precise positioning of the microscope is performed. Then a moving mirror scans the section of a magnified line image and light beams are reflected from the mirror and are directed through a slit to the photoamplifier. The line signal derived from the photomultiplier is displayed in the *XY* plot mode. The horizontal input representing the scan, is related to actual position of the mirror, while the vertical axis represents the light intensity level. Therefore we can see the profile of a line image and its position respect to the centre of scanning interval. The photoelectrical microscope allows detecting the position of the line centre with uncertainty of 2 nm depending also on the quality of graduation lines. High quality lines have equal width and sharp edges in the range from 1 µm to 10 µm.

In the dynamic calibration systems all the data are collected when the microscope carriage is moving. The carriage speed at the graduation line is typically lower. Between the lines a higher speed, up to 20 mm/s [1], can be used.

Line scale calibrations with slit microscope in dynamical mode of operation have been conducted at the PTB.

Line scale calibrations with moving CCD microscope have been carried out in Finland at the Centre for Metrology and Accreditation (MIKES) length calibration laboratory [5].

During a preparatory run, the program moves the microscope toward a given graduation line and examines the intensity sums of certain picture elements of limit, the line is found and the program calculates an approximate counter reading for the graduation line. In the actual measurement the program monitors the counter reading, and when the microscope is close to the graduation line the program stores the current reading, starts analog-digital (A-D) conversion of the interference and triangle signals, and triggers the frame grabber to digitize the next two video fields.

When the nominal position of the line is reached i.e. the line is within the field of view of CCD camera, the computer gives the command to perform an image acquisition and reads the value from the interferometer in real time. While the microscope continues to move to the next line, the computer processes the CCD image and calculates two values: the position of the image of the line which is read out from the interferometer and the position of the middle of the line in the image that is calculated from a mean profile of the line by summing several lines. The middle point is obtained by performing linear adjustment on the edges that are delimited by a low threshold and a high threshold. This method allows good measurement results if the profile of the line is symmetrical and the number of points for regression is high enough. For the determination of true position of the line the magnification of microscope and the camera has to be calculated, therefore two successive images of the same line are taken. The program also collects environmental data continuously and calculates the refractive index of air for every set of graduation-line data. The refractive index of air is calculated by the modified Edlen formula. The profiles of a graduation line taken with a moving CCD microscope are shown in Fig. 4.

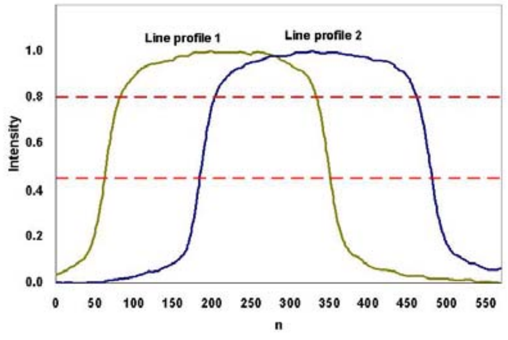

Fig. 4 Line profiles obtained by photoelectric microscope with CCD; an image magnification of 25x

The computer program calculates the magnification

$$G_i = \frac{L_{2i} - L_{1i}}{P_{2i} - P_{1i}}$$

where P_{1i} and P_{2i} are positions of the middle point of the1st and 2nd line in the image, in pixels; L_{1i} and L_{2i} are inreferometer values of positions of the line image in mm.

The pitch value or mean distance between two successive lines (*i* and *j*) is determined by

$$D = \frac{L_{2j} + L_{1j} - L_{2i} - L_{1i}}{2} + G_j \frac{P_{1j} + P_{2j}}{2} - G_i \frac{P_{1i} + P_{2i}}{2}$$

The actual analysis procedure also takes into account changes in the wavelength λ during the measurement. Finally, the measured length is normalized to 20°C by the use of the thermal-expansion coefficient and the measured scale temperature.

6. Experimental results

6.1 Encoder

The measurements of high-precision linear encoder have been carried out at PTB in air-conditioned measurement room with a room temperature of 20°C.

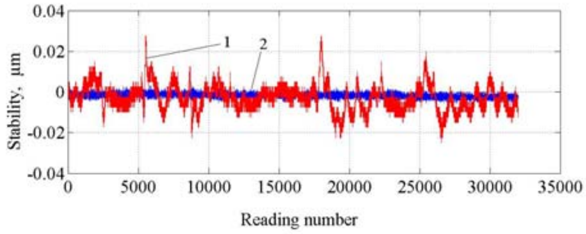

Fig. 5 Stability of laser interferometer and reference encoder in static mode: *1* - laser interferometer; *2* - linear encoder

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. The comparison of measurement fluctuation of both systems in air-conditioned laboratory is presented in Fig. 5.

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. 5 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 magnitude 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. 6. Repeated measurements on different positions of the line scale displayed quite similar results. Therefore the correction of measured value of the reference system for further investigations is not needful. It is evident that, even in the finely air-conditioned laboratory environment, the low heat capacity of the air causes quick changes in temperature that can lead to relatively large fluctuations in the measured values obtained from laser interferometer, therefore performing measurement in dynamic mode, i.e. in shorter time is important to avoid the influence of temperature changes. The comparatively short distances between encoder‘s scale and index grating also minimize the sensitivity to environmental factors.

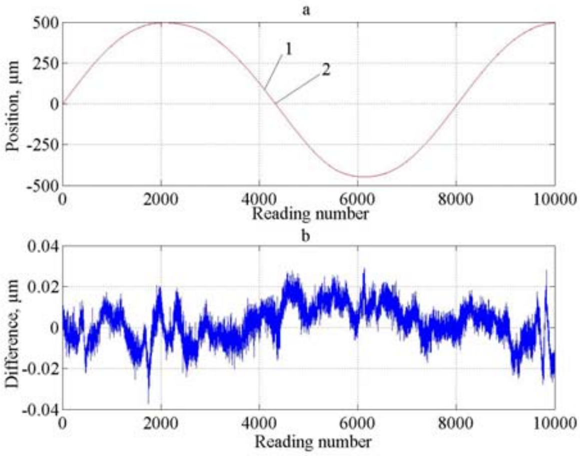

Fig. 6 Length measurement variations (discrepancy between readings of linear encoder and laser interferometer) in dynamic mode: *a* - position readings: *1* - laser interferometer, *2* - linear encoder; *b* - difference between position readings of *1* and *2*

6.2. Moving CCD microscope

A set of measurements was conducted for the investigation of dynamic calibration capabilities of graduated line scales. The comparator setup at MIKES with a moving microscope and electrically shuttered CCD camera was used for detection of the line scale graduation. The microscope and the CCD camera are mounted on a carriage and the microscope is adjusted perpendicular to scale plane within 0.2^{o}. The microscope carriage is pulled by a direct current (DC) motor along the stone rail on the air bed. The line scale is aligned under the microscope to a position at which the appropriate graduation lines will be in focus. The position of the microscope is measured by laser interferometer placed on a vibration-isolated stone table.

Measurements were performed with calibration speeds ranging from 15 mm/s up to 20 mm/s and distances between successive graduation lines varying from 1 mm to 4 mm. The number of runs was set at 5 and all the data were collected when the microscope carriage was moving. The averaged positions of different graduation lines measured with different speeds are showed in Fig. 7. It is clearly seen that speed variations have no influence on measurement results. Higher measurement speed was mainly limited by the design of the microscope carriage drive.

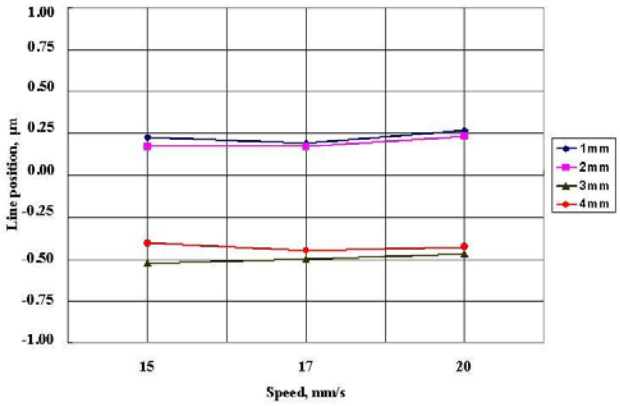

Fig. 7 Average line position measured with a moving microscope at different measurement speeds

6.3. Slit microscope in dynamical regime

A slit microscope equipped with CCD camera and laser distance sensors was used for the investigation of line structure detection in dynamic mode too. Laser distance sensors are used to keep microscope in focus. The reflected light from the scale after slit is detected by photomultiplier and measured by A/D converter simultaneously to the laser interferometer readings. The line scale on the carriage was moved with shifting velocities.

The repeatability of three consecutives measurements of the scale at certain speed is shown in Fig. 8 as the deviation from the mean of these measurements. The measurement results obtained with this setup revealed quite similar dynamic characteristics in terms of repeatability (see Fig. 7) compared with the comparator using microscope with CCD camera.

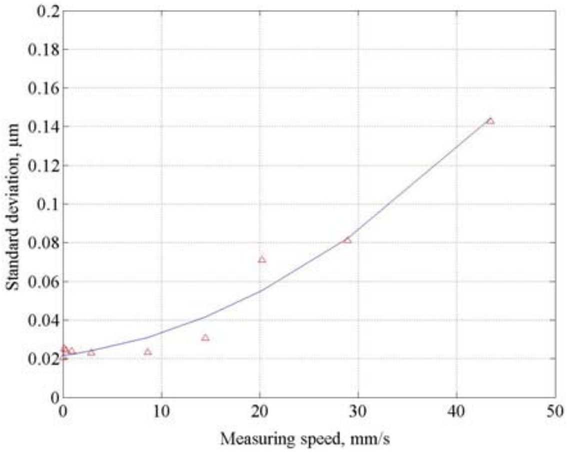

Fig. 8 Line position deviation vs speed measured with photoelectric microscope

With the help of these different measurement setups it can be ascertained that the investigated measurement systems operate reliable at velocities up to 15-25 mm/s. Whenever the measurement system is not able to count fast enough, the measurement error from period to period is getting larger. Owing to the experiments carried out it has been concluded that the measurement speed up to 20 mm/s and more could be reached without sensible loss in measurement accuracy. The limiting factor is basically the driving mechanics that can hardly be used at higher frequencies. The influence of geometrical errors on performance of the measurement system and its nonlinearities can be determined by arrangement of the scanning system.

7. Conclusions

A measuring device - precision 1D comparator - for the 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 for the measurements. 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 the accuracy smaller than 30 nm can be carried out in dynamic mode and line position detection accuracy does not depend on the measurement speed fluctuations in the range of 0-25 mm/s. The use of modern CCD cameras enables us to define measurement points more precisely and lead to greater improvement of dynamic characteristics of length calibration systems. Using multi-channel temperature and control system the impact of thermal interferences for the test item can be evaluated.

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BRŪKŠNINIŲ ILGIO MATŲ KALIBRAVIMO GALIMYBIŲ TYRIMAS

Reziumė

Straipsnyje nagrinėjama matavimo sistema, skirta tikslių linijinių keitiklių savybėms tirti ir jiems kalibruoti. Atlikti bandymai su keitikliu su fazine difrakcine gardele, suformuota stiklo keramikos Zeroduro paviršiuje bei palygintos sistemos ir lazerinio interferometro charakteristikos. Rezultatai parodė, jog keitiklio matavimo rezultatai pasikartoja kur kas geriau, be to, jis yra ne toks jautrus aplinkos sąlygų pokyčiams, palyginti su lazeriniu interferometru. Taip pat atlikti eksperimentai siekiant įvertinti brūkšninių ilgio mato kalibravimo dinaminiu režimu galimybes panaudojant komparatorius su plyšiniu mikroskopu bei CCD jutikliu. Sukurtos matavimo priemonės leidžia atlikti precizinius matavimus iki 25 mm/s greičiu, tiksliau ir našiau įvertinti linijinių skalių metrologines savybes.

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INVESTIGATION OF CALIBRATION FACILITIES OF PRECISION LINE SCALES

Summary

The paper describes the development of measurement setup for the characterization and calibration of precision incremental linear encoders. An exposed linear encoder with a phase grating applied to a carrier of glass ceramics Zerodur has been tested and its performance in respect of laser interferometer was compared. It has been proven that the system displays better reproducibility and lower sensitivity to the ambient conditions variations compared with a laser interferometer. Experiments using comparator designs with CCD microscope and slit microscope have been conducted to investigate dynamical capabilities of graduated line scales calibration. The measurement facilities developed allow high precision measurements with velocities up to 25 mm/s and enable us also to more accurate and effective evaluation of metrological properties of the line scales.

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ИССЛЕДОВАНИЕ СРЕДСТВ КАЛИБРОВКИ ЛИНЕЙНЫХ ШКАЛ

Резюме

В статье исследуется создание установки измерения для характеристики и калибровки точных инкрементальных датчиков. Были проведены опыты с бесконтактным датчиком с фазовой решеткой на стеклянной керамике Зеродур и его характеристики сравнены относительно лазерного интерферометра. Было доказано, что система показывает лучшую воспроизводимость и более низкую чувствительность к изменениям окружающей среды по сравнению с лазерным интерферометром. Также проведены эксперименты используя компараторы с щелевым микроскопом и CCD микроскопом для исследования динамических способностей калибровки линейных шкал. Развитые средства позволяют проводить измерения со скоростями до 25 мм/с, а также более точно и эффективно оценить метрологические свойства линейных шкал.

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