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Software based control techniques for precision line scale calibration

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ABSTRACT: **A precision line scale calibration method in a dynamic regime enables to gain the calibration throughput and simplify the comparator's structure and control. However, the errors featured by geometrical deviations, static and dynamic loads as well as temperature induced deformations should be considered and incorporated into uncertainty budget. These errors contain random and systematic components and can be minimized by increasing the accuracy of system design and implementing numerical error compensation methods. The paper discusses advances of precision line scale calibration system design gained by implementing new measurement and software based control techniques.**

1 Introduction

One of the most complicated fundamental problems that science and the high-tech applications confront today is the length calibration ones where the new and difficult-to-implement requirements posed by the embedded metrology needs can be met only by developing novel systems that absorb recent scientific and technical findings and optimally comply with specific calibration requirements as well as by improving existing calibration systems open to complying with fundamental principles of precision engineering. The need for productivity improvements in line scale calibration ultimately drives the demand for technologies, which permit to embed the traceable length metrology directly into technological processes by performing precise dynamic measurements in more demanding environments [1].

The paper presents the results of broad-scope investigations to develop a new long-stroke comparator to offer traceable calibration of the line scale. The contribution is a part of the national program supported by Lithuanian State Science and Studies Foundation.

The research of length calibration systems and complex investigation of calibration process enabled us to validate reasoned schematic, structural and constructive solutions for interferential laser comparator that meets certified requirements for the national line scale standard.

Results of the research were used for the design of traceable line scale calibration system operating in a dynamic mode maintained by JSC "Precizika Metrology" that would meet higher requirements for calibration efficiency and accuracy.

2 Description of the system

The comparator, presented in Fig. 1, is developed to calibrate line graduation scales and incremental linear encoders. It consists of four main parts, namely the body of the machine, a laser interferometer, a translating system and a detecting apparatus.

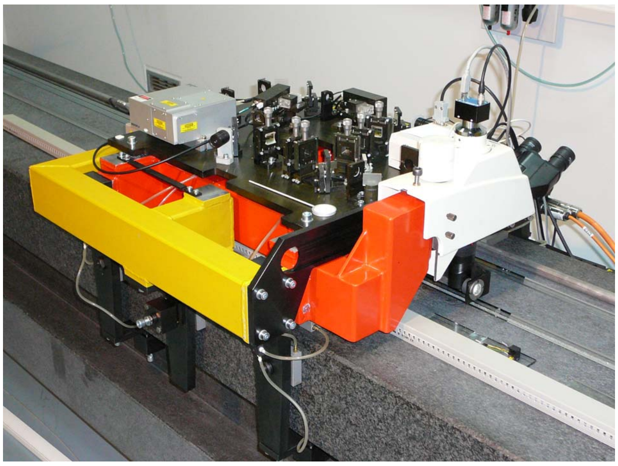

Fig. 1 Precision measurement carriage with CCD microscope

The body of the machine, which is made of granite surface plate, is used as the base of the machine and as a guide for the moving carriage. Measurement of the displacement of the carriage is realized by laser interferometer that consist of Zygo ZMI 2000 laser head and interferometer with the single-pass arrangement. The interferometer provides a resolution of 0.62 nm.

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A moving CCD microscope serves as structure localisation sensor for the measurements of line scales. For precise and full-scale evaluation of the application of dynamic mode of the line scale calibration a CCD-microscope based edge detection system has been developed. The system uses a modular focusing unit to capture image data and incorporates a set of high-quality objectives and image-processing software.

The angular control loop - together with the numerical procedure - has been applied to compensate and reduce the Abbe uncertainty contribution. The comparator was designed to achieve expanded measurement uncertainties ($k = 2$) down to 7×10^{-7} m ($L = 1$ m) in dynamic regime. It enabled to trace the calibration of line scale of up to $L \leq 3.5$ m long to the wavelength standard. The magnification and numerical aperture of the NIKON objective lens used is 20× and 0.4 respectively. The microscope on the carriage guided on aerostatic bearings is moved with a controlled velocity of 1 – 10 mm/s [2].

Line scales are calibrated by making carriage displacement measured by the interferometer, correspond exactly to scale interval lengths. The translating system, which carries the retroreflector, angular mirror and CCD microscope for detecting the measuring points, provides relative displacements between the linear artefact and the detection system. The latter consists of a guiding carriage, guided frame, and NIKON modular CCD microscope fixed to the frame. The friction gear drives the guiding stage, which incorporates air bearings for smooth movement. It has a traverse length of 3500 mm.

3 Control system of the comparator

The operation of the comparator is controlled by a personal computer running under Windows operation system as shown in Fig. 2. The concept of control system is based on modified software of the coordinate measurement machines which runs on a central PC. The software handles the user interface, the control of the measurement process and can be used for data evaluation. The computer handles the position control of the microscope carriage and is used for measurement data acquisition purposes. The PC is used to process images of the CCD microscope and other time critical measurements like the sampling of measurement values from the interferometer.

Length comparators are only using a photoelectric microscope for the detection of structures on artefacts. Therefore it is possible to write a complete software package for data acquisition. The calibration of complete measurement system with own electronics is more complex to handle. The software of the line scale comparator has a driver interface and different routines for control of the measurement systems. For a high acquisition speed the standard drivers are running in a real time extension. Because it is not possible to handle every electronics interface or the effort for the customer is too large to provide a driver, a separate computer system can be used, if it is able to acquire and store results on a trigger pulse for offline calculation.

For a detection of the line position reading of the laser interferometer and image of a line structure captured by CCD camera are necessary. Therefore synchronized data reading from both CCD camera and laser interferometer is a precondition for capturing images in dynamic regime [3].

Trigger signals can be generated by a timer, by software or by measurement systems at specified events. For high speed data acquisition, a real time extension can be used to avoid time delays by the Windows operating system. Basically there are two methods for generating a trigger event. Firstly, the signal is generated by the controller, and secondly, the impulse is produced by the positioning system. The controller periodically requests the laser interferometer and memorizes the distance of the microscope carriage thus the following position of the carriage could be calculated. When the foreknown position is reached the controller will generate a synchropulse. This method is applicable when the carriage speed is very uniform.

In the other method, the positioning drive is counting impulses received from the resolver, and after a certain number of gained signals the reading of CCD camera and interferometer data is synchronized. After the synchropulse the data from the interferometer and camera are stored in the computer for further processing and calculations.

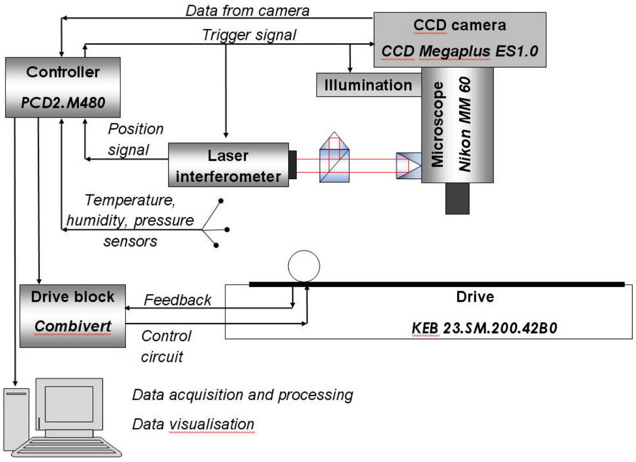

Fig. 2 Control system of the line scale comparator

Laser interferometer has two data exchange channels: RS232 serial and P2 parallel interfaces. Digital camera transfers data through IEEE1394 serial interface. Both devices have special inputs for synchronization.

Data transfer rate of RS232 interface of the laser interferometer is not sufficient therefore controller with parallel 32-bit P2 interface for data acquisition is implemented. Sampling time of this interface is about 200 ns, but the data is accessed in two 16-bit transfers. Data transfer time amounts up to 32 µs, and this results in maximal sampling frequency 30 kHz. With 3 mm/s calibration speed the data from the laser interferometer is read within 0.1 µm. The CCD camera's sampling time of about 20 µs corresponds to the image shift of 60 nm. Given the pixel element of the CCD matrix at magnification of 20x equal 0.3324 µm, the contribution of the CCD sampling rate is not significant and can be treated as systematic error when the speed of the microscope carriage is constant. The third element that influences the measurement process is illumination system of the microscope. Lightning time of the bulb shouldn't exceed 10 µs.

4 Experimental results

For high precision systems the metrology loop and the structural loop(s) should exist separately and independently to the greatest practical extent in order to reduce errors by partially or entirely eliminating certain loads (force or heat) from the metrological loop. Preferably, separation would be a physical one, but it could also be an informational separation, for example, through error compensation circuits based on measurement of structural models.

One of the primary tasks in the design of high precision machines is giving heed to the Abbe principle, which requires that the displacement measuring system should be in line with the functional point which displacement is to be measured.

A change of the tilt angle of the slide during measurement causes a first order error, the so called Abbe error, if the measurement axis of the interferometer and the calibration object are not identical. To minimize the Abbe error the angular variation of the measurement reflector is measured and the correction for the Abbe offset is performed numerically since the offset distance is known. The structural components for Abbe error correction include additional interferometer axis for measurement of angular deviations of the microscope carriage.

From economic point of view it is reasonable to secure the precise linear motion by means of precision manufacturing when linear errors in X and Z directions do not exceed several micrometers, and angular deviations amount up to several arc sec. Further error compensation can be carried out by employing software error correction [4].

Geometrical errors can be reduced by means of computational and active methods of error compensation.

In the first case the movement errors are measured and approximated by parametric functions, measurement error-to-movement errors dependence models are created, and errors are compensated in accordance with those models on the real time scale. The value of residual errors depends on the stability of movement and the accuracy of approximation of their systemic components by parametric functions.

In the case of active error compensation the compensational values of the angular fluctuations of the carriage are determined in accordance with the difference of the displacement of two various points of the carriage on the compensation plane.

To obtain the data for the numerical compensation, the angular fluctuations of the carriage were measured with a laser interferometer at steady scale calibration speed of 4 mm/s. Measurement results of the angular deviations of the measurement mirror are depicted in Fig. 3.

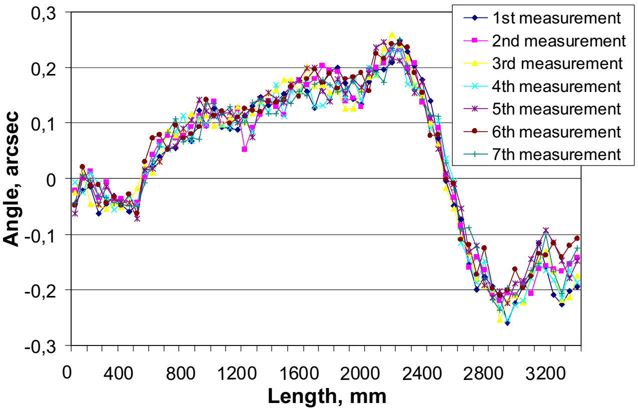

Fig. 3 Interferometer signal for Abbe error correction

Repeated measurements revealed a good repeatability of angular error along the travelling range of the microscope carriage. The angular deviation ranged about 0.5 arc sec for the travel of 3250 mm. Fluctuations induced by elastic vibrations of the structure and other sources amount to 0.07 arc sec.

For precision line scale measurements quantitative analysis of line profile images high quality digital images are necessary. The accuracy of images captured by photoelectrical microscopes is limited by the accuracy and stability of geometrical dimensions of optical components as well as the capabilities of digital imaging. Due to the geometrical errors of the comparator and bending of the scale, microscopes with high numerical aperture need an autofocus mechanism. Guidance deviations of the translation mechanism results in first order length measurement errors and the stability of the microscope is reduced. It also results in defocusing of the microscope.

To solve this problem a defocusing sensor with dynamical focussing based on astigmatic detection [5], can be applied. This detection principle is symmetrical around the optical axis and does not exhibit any preference of direction. Technical surfaces can be measured in any direction and measurement results are independent of direction.

The results of modelling [6] and calculations performed in order to evaluate both the influence of defocusing of scanning mechanism and angular alignment errors resulting from mechanical deformations of line scale or microscope construction are displayed in Fig. 4.

It has been proven that even relatively small angular misalignment increases the error of line centre detection significantly when microscope is out of focus. Therefore, the influence of geometrical errors on performance of the measurement system and its nonlinearities should be compensated by a proper arrangement of the scanning system and the line scale and the use of software compensation.

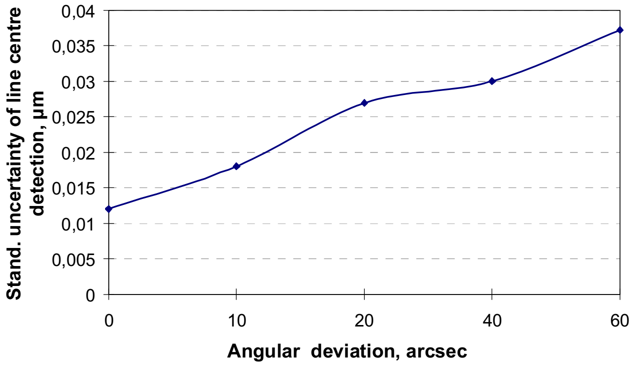

Fig. 4 Standard uncertainty of line centre detection with CCD microscope

Measurements performed at German national metrology institute PTB Nanocomparator laboratory have affirmed that defocus of 3 µm leads to a shift of 30 nm in the position of the line. It is a typical result obtained with Nikon objectives that are used for the line scale comparator as well. The influence of defocus seems not to depend on the magnification of the objective [7].

After the system upgrading the measurements of line scales were reassumed. A 3200 mm length glass line scale with pitch of 20 µm was calibrated. The repeatability of five consecutive measurements of the line scale is depicted in Fig. 5 as the deviation from the mean of these measurements. Standard deviation was reduced to about 0.16 µm.

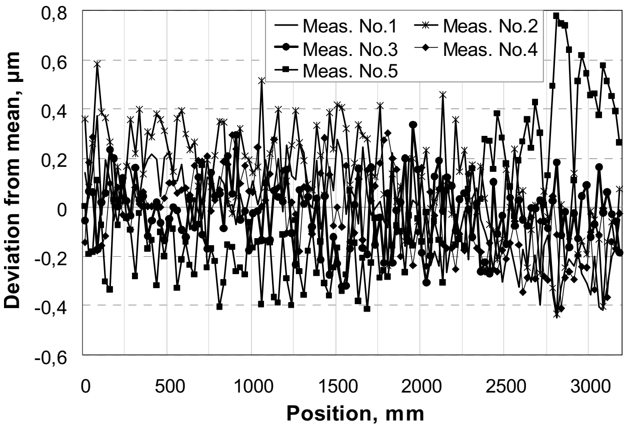

Fig. 5 Repeatability of line scale measurements

The spread of the measurement results at both ends of the scale can be explained by larger time-depended temperature gradients resulting from the heat sources (laser and laboratory floor with varying temperature).

5 Conclusions

Small elastic deformations induced by dynamic processes as well as geometrical errors of the comparator components can significantly reduce the measurement accuracy of the system and therefore have to be eliminated by proper alignment of the scanning system and the line scale and the use of error compensating techniques.

Geometrical deviations can be reduced by means of software based methods of error compensation. Given the active method is applied, the angular fluctuations are directly measured and the errors resulting from them are compensated in real time, providing improved accuracy of the line scale calibration system.

The structural components for compensation of Abbe error at the line scale comparator have been implemented, and the measurements conducted have revealed that repeatability of the angular measurements is good enough, and residual errors of the microscope carriage are stable to substantially reduce the Abbe error by performing the active numerical compensation of the guideway deviations.

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