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Refinements of Precision Line Scale Calibration System

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Abstract

The paper treats the issue of embedding the traceable length metrology into technological process by performing precise dynamic measurements of line scale in its manufacture line. It addresses the error-related problems specific to line scale calibration in dynamic mode of operation that are caused primarily by dynamic loads. The precision line scale calibration in dynamical mode of operation is considered. Modal analysis performed and measurements conducted of the spatial vibrations of comparator structure revealed that dynamically-induced errors can noticeably contribute to the measurement uncertainty budget.

The contribution was focused on the investigation of both the accuracy of the graduation line detection and the line scale calibration repeatability error reduction. The calibration experiments were performed that intended to document current capabilities to carry out line scale calibrations on high quality graduated scale made on low thermal expansion substrate.
KEY WORDS: *line scale calibration, measurement uncertainty.*

1. Introduction

The relevance and necessity of addressing the problem of precision and high-speed line scale calibration is primarily driven by the rapid increase of demands on calibration accuracy and throughput of precision scales. 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 than those of calibration laboratories, providing metrological traceability of accuracy parameters of precision scales to the primary length standard in their manufacture line and reducing both the uncertainty of the scale calibration and calibration process duration [1, 2].

Throughput limitations for calibration systems in question are featured by the whole complex mechanical system including error compensation circuits. Therefore, satisfying new demanding and contradictory requirements of high-speed and accuracy for precision line scale calibration calls for the necessity of in-dept analysis of the uncertainty budget including dynamics-induced errors caused by measurement speed fluctuations, time delays, noise and vibrations especially during the graduation line detection. The broad-scope efforts are needed in order to investigate these systems in specific work environments and above all to model small deformations properly. Structures of precision length comparators often are too sophisticated to be modelled precisely by applying simple methods. Complex physical models, finite element models (FEM), and engineering ones as well as their analysis tools are to be developed and applied in order to perform qualitative and quantitative description and analysis of determinants of the precision line calibration process.

The paper describes the recent joint work performed at Kaunas University of Technology and JSC “Precizika-Metrology” aiming at embedding the traceable length metrology into technological process of the precision line scale calibration. We handle the refinement of the precision calibration system design by analyzing the elastic deviations of the structure localization system. In this paper, we will describe the key points of the current design of the line scale comparator and the measures taken to reduce its uncertainty contributions.

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2. Recent developments of comparator

The comparator presented in Fig. 1 is developed to calibrate line graduation scales and incremental linear encoders. It consists of the body of the machine, a heterodyne laser interferometer, a translating system and a detecting apparatus. A moving CCD microscope serves as structure localization sensor for the measurements of line scales. 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 ≤ 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. The design and capabilities of the comparator is described more detail in [3, 4].

Fig. 1 Experimental setup of the length comparator and the microscope

The dynamic behaviour of the line scale comparator carriage has been investigated, [5, 6] in specific operating modes in order to determine the capabilities of increasing calibration speed and gaining calibration throughput. Means for shortening graduation line detection time were designed and implemented. In-depth analysis of specific errors inherent in dynamic calibration and compensation possibilities for predominant errors, performing experimental research enabled us to determine the correlation between calibration accuracy and measurement speed.

The dynamic calibration error originating due to vibration sources and temperature variations have been identified as the major error sources that should be considered and implicated in the uncertainty budget while embedding the traceable length metrology directly into technological processes. Therefore the comparator system has been modified in order to reduce the contributions of dynamic-induced errors and temperature variations to uncertainty budget of line scale calibration system. Functional capabilities of the comparator were expanded by:

- implementation of new driving system of the microscope carriage,
- modification of coupling mechanism between the master and slave frames of the carriage,
- replacement of the microscope support that enabled adjustment of the measurement field in transverse direction,
- redesign of the junction between interferometer retroreflector and microscope carriage.

The dynamic behaviour of the optimized line scale comparator carriage has been investigated by both finite element modelling and experimentally. The combined output of this broad-scope effort was nearly an order of magnitude reduction in calibration uncertainty.

3. Modelling

A new 3D finite element model of the microscope carriage has been developed in order to both investigate the influence of dynamical excitations of a long-stroke comparator structure and evaluate the possible influence of transitional and steady vibrations on the graduation line detection during calibration in dynamical mode of operation. The investigation has been performed by ANSYS finite element software, [5, 6]. Modal analysis of the spatial carriage and microscope deviations induced by seismic excitations as well as those caused by operation of the carriage drive vibrations has shown that dynamic factors may contribute significantly to the calibration uncertainty budget. To minimize, in particular, the vibrations of the measurement reflector the construction of the carriage structure was optimized and drive-originated were vibrations reduced.

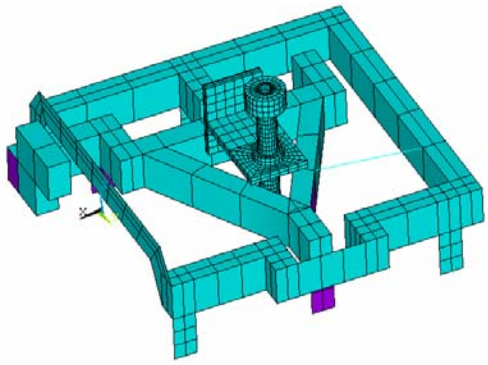
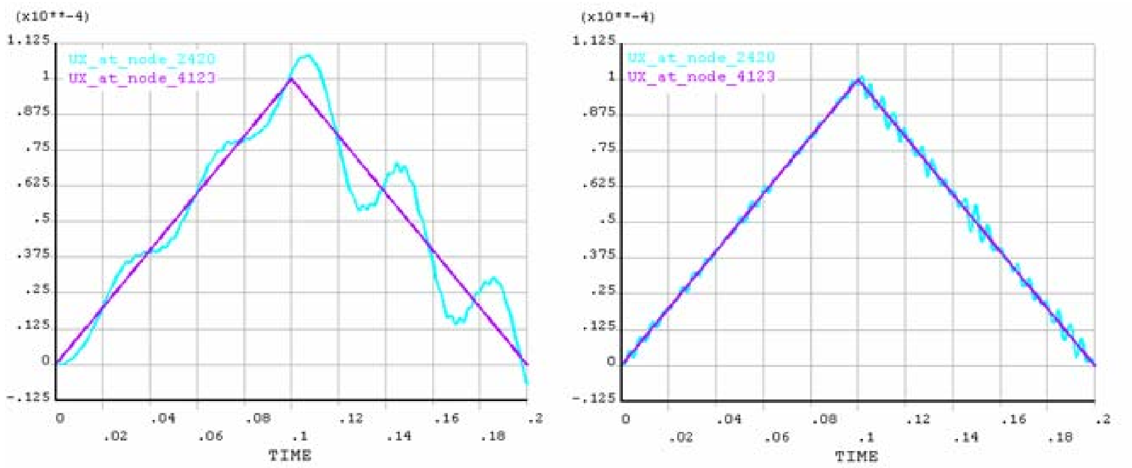


Fig. 2 Finite element model of the microscope carriage

Finite element models corresponding to several schemes of junctions fixations between master and slave frames as well as between the slave frame and the microscope were developed and compared. The improvement of the dynamic behaviour of the structure by locating the microscope support to the centre of the slave frame and proper positioning of the junction between the frames of the carriage leads to much more favourable modal spectrum. The FE model of the optimized microscope carriage is presented in Fig 2.

The transient vibrations of the measuring point of the microscope due to excitation of the start stop movement of the carriage drive are presented in Fig. 3 a, b. Given the input pulse of the 200 ms duration the amplitude of undesirable vibrations may amount to 0.15 – 0.20 of the displacement amplitude. As it can be clearly seen from comparison of the measurement data presented in Fig. 5, a and Fig. 5, b, the reduction of vibrations caused by the carriage drive can be substantial.



a b

Fig. 3 The responses of the structures to the displacement pulse generated by the drive; a) nonoptimized structure; b) optimized structure

4. Experiments

Extensive investigations were accomplished to both reduce the dynamically induced deviations originated by the dynamic excitations of the mechanical structure and optimize the comparator design.

The precision measurements were performed in order to evaluate the impact of small vibration on performance of the line scale calibration process. The experimental results revealed, in particular, that the sample standard deviation of the drive-induced relative displacements between the moving reflector of the interferometer and the measurement point of the microscope may reach 0.662 µm (at calibration speed 3 mm/s), [6, 7]; they were considerably reduced by optimization the carriage structure and elimination the undesirable modes of vibration.

Horizontal vibrations of the measurement mirror have direct impact to the measured position of the microscope. The vibrations of the interferometer measurement mirror were measured using the heterodyne interferometer when the microscope carriage was not moving, but the aerostatic bearings and driving motor were switched on. The carriage was placed near the laser interferometer in order to reduce the influence of environmental parameter variations. The whole measurement process lasted 31 s, and 1000 interferometer values have been taken. Measurement results depicted in Fig. 4 show an improvement of systems stability using the optimized microscope carriage structure (blue line). The sample standard deviation of the drive-induced relative displacements of measurement mirror was reduced from 0.178 µm (measurement results 2007.11) down to 0.054 µm (measurement results 2008.11).

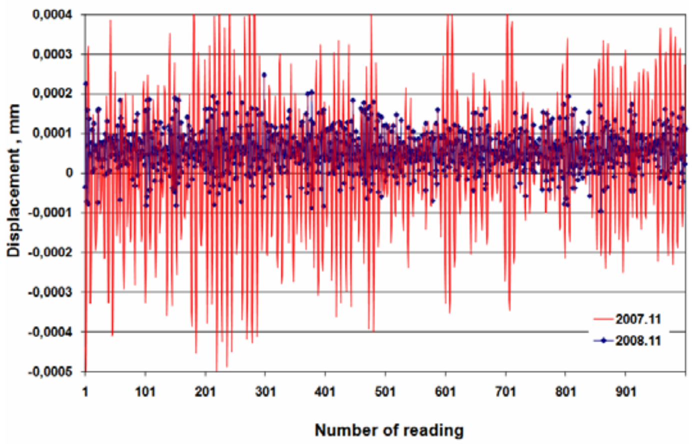


Fig. 4 Comparison of vibrations of the interferometer measurement mirror

The calibration experiments were performed that intended to document current capabilities to carry out line scale calibrations on high quality graduated scales made on low thermal expansion substrate. The line scale standard made of the glass ceramic Zerodur was available for calibration purpose from PTB. The dimensions of the scale are 230 mm in length, 20 mm in width and 14 mm in height. The graduation represents a total length of 200 mm and consists of line structures with 1 mm length and 2.5 µm width. The line structures are reflecting on transparent substrate.

The measurand that was determined on the line scale standard is the deviations from the nominal lengths for 1 mm lines (1 mm pitch). Fig. 5 shows the deviations from the nominal positions for the weighted mean, calculated on the basis of the set of 6 independent measurement runs taken at the microscope carriage speed 3 mm/s. The environmental chamber and scale temperatures were held within ± 0.05 °C during the measurements; the average atmospheric pressure was 99825 Pa, and the average relative humidity was 50%.

The positions of the line were corrected for the influence of the temperature deviation from 20 °C and pressure deviations from 1013.25 hPa.

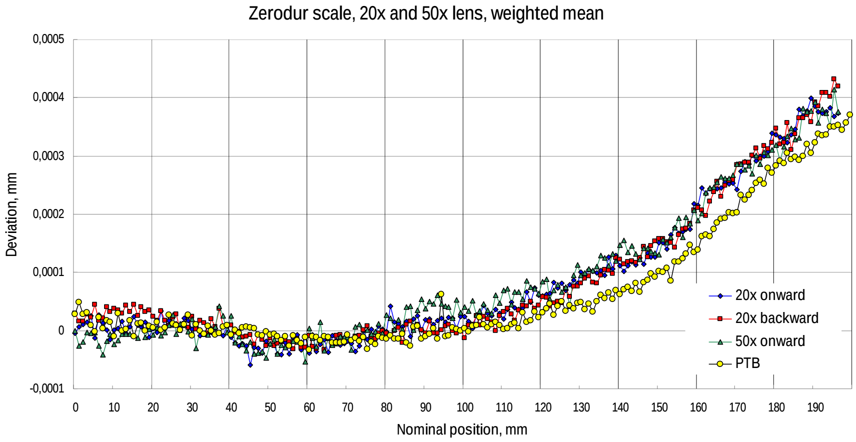


Fig. 5 Calibration results on Zerodur scale, 200 mm graduation, 1 mm step

5. Conclusions

Key points of the current design of the line scale comparator and the measures taken to reduce its uncertainty contributions were discussed in this paper. Advanced FE modelling techniques were applied and experimental investigations were performed in order to represent the improved dynamical behaviour of the comparator. A new FE model has been developed and an influence of dynamic processes in the length comparator structure has been evaluated. The modelling tools developed enable us to represent the structural behaviour of the calibration system and ensure a high level of the model adequacy to the reality.

The dynamic behaviour of the line scale comparator carriage has been investigated by both finite element modelling and experimentally. Computational analysis revealed the basic causes of the undesirable mechanical vibrations conditioned by external seismic actions and vibrations induced by the carriage drive. The qualitative conclusions derived from numerical solutions were in close correlation with experimental results.

To investigate the actual measurement performance of the refined comparator system a high quality graduated scale made of low thermal expansion substrates was measured and compared with results from other (PTB) comparator; an agreement of about 50 nm has been reported.

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