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# REDUCING DYNAMICALLY-INDUCED DEVIATIONS FOR LINE SCALE CALIBRATION IN NON-IDEAL MEASUREMENT SITUATION

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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. Introducing the dynamic regime of calibration leads to the dynamic calibration error originating due to vibration sources in the structure. This uncertainty contribution should be considered and implicated in the total uncertainty budget. A new 3D finite element model was developed in order to both investigate the influence of dynamical excitations of a long stroke comparator structure and evaluate possible influence of vibrations on geometrical dimensions of the line scale. Both the dynamically induced deviations and current capabilities to carry out line scale calibrations were examined experimentally. The experiments were conducted on the interferometer-controlled comparator setup with a moving microscope that was further developed to reduce the calibration repeatability error.

**Keywords** : embedded metrology, line scale calibration

## 1. INTRODUCTION

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.

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 meet the specific calibration requirements as well as by improving existing calibration systems open to complying with fundamental principles of precision engineering, [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 (FEM) models, and engineering ones as well as their analysis tools are to be 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.

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## 2. FEM SIMULATIONS

The vibrations of the measurement carriage system due to both the seismic excitation and the excitations induced by the carriage drive can be characterized by investigating the linear vibration modes of the mechanical structure, [3-6].

The microscope carriage system of the line scale comparator consists of two carriages guided on aerostatic bearings – the guiding carriage and the guided inner frame,

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(the measurement carriage). Thus, the structural loop and the metrology loop are physically separated in the comparator, and carriages are interconnected only by a rod link.

In this contribution, the finite element (FE) technique was applied in order both to evaluate the elastic displacements of the carriage system that are governed by the dynamic excitations and optimize the mechanical design. The modal vibrations of the carriage were investigated by using the finite element model, Fig.1, developed in ANSYS finite element system.

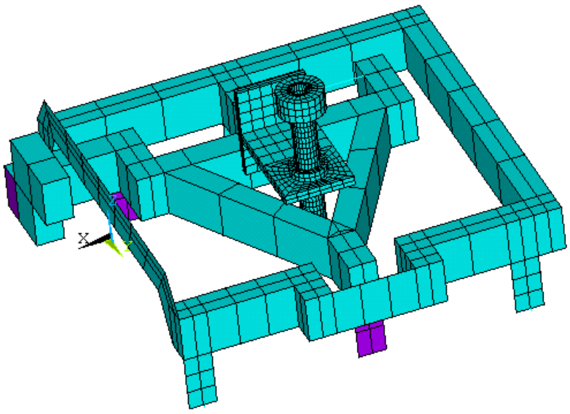

Fig. 1. FE model of the microscope carriage.

Among large number of vibration modes in the range 0-100 Hz three modes have been identified as highly influencing the deviations between the linear artefact and the line detection (structure localisation) system:

1. the shear elasticity of the guiding frame, which causes considerable amplitudes at frequency range close to 35 Hz;
2. the elasticity of the aeroelastic bearings;
3. the elasticity of the support of the microscope, the construction of which is similar to a cantilever attached to the guided frame.

Finite element models corresponding to several schemes of junctions fixations between guiding and guided frames as well as between the guided frame and the microscope are presented in Fig 2-4.

The shear mode of the guiding carriage, presented in Fig. 2 is characterized by considerable coupling between vibrations of both carriages and demonstrates large displacements of the microscope measuring point in the direction of the scale calibration. The mode is inevitably excited during start-stop motion of the carriages as its displacements at the place of attachment of the carriage drive are quite large.

Other two modes displayed in Fig. 3 and Fig. 4 are of similar natural frequencies, namely 70 Hz and 76,5 Hz. The mode depicted in Fig. 3 is conditioned by the elasticity of the aerostatic bearings, while the mode in Fig. 4 is governed mainly by structural elasticity of the carriage system. The presence of both modes leads to considerable deviations of the structure localization system. The interaction of the two modes seems very likely at certain conditions and may cause undesirable effects on the comparator operation.

The developed model has been used for investigation of possibilities to improve the dynamic behaviour of the system.

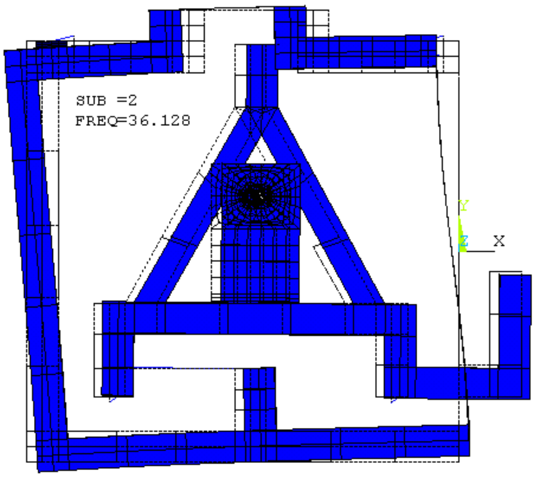

Fig. 2. The shear mode of the guiding carriage.

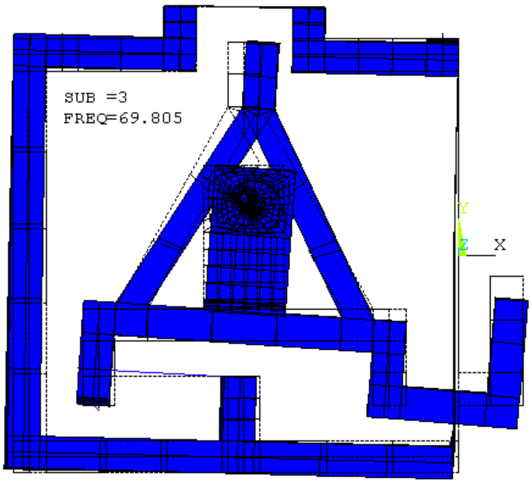

Fig. 3. The mode caused by the elasticity of the aerostatic bearings.

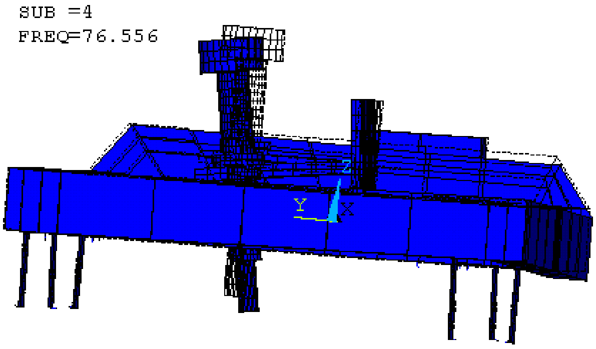

Fig. 4. The mode caused by structural elasticity of the carriage.

The analysis of the FE modelling results have demonstrated that maximum displacements in the direction of carriage motion are obtained at the measuring point (apex of the microscope lens); due to dynamic excitations they can amount to >100 nm and may cause detection errors in determining positions of graduation lines.

The refinement of the carriage design by locating the microscope support to the centre of the guided frame and proper positioning of the junction between the frames of the carriage system leads to much more favourable modal spectrum and ensure the minimum influence of the vibration of the guiding carriage as well as the strong reduction of the microscope deviations under consideration.

## 3. EXPERIMENTAL INVESTIGATIONS

The experiments were carried out on the measurement machine dedicated to the one dimensional calibrations of line scales and linear encoders, Fig. 5.

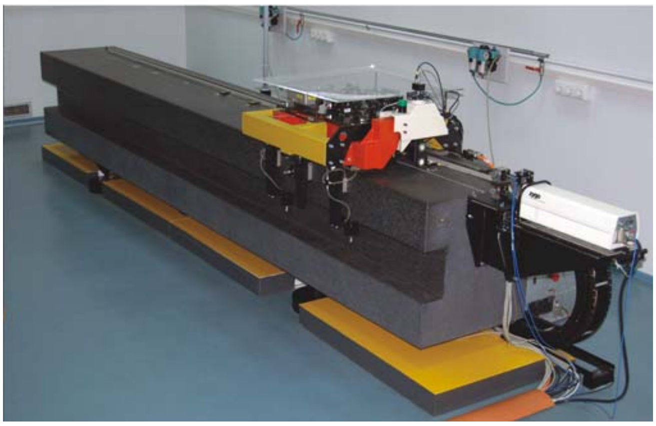

Fig. 5. Interferometer-controlled line scale comparator with moving CCD microscope.

The calibration system enables to trace the calibration of line scale of up to L ≤ 3,5 m long to the wavelength standard. The comparator was designed to achieve expanded measurement uncertainties (k = 2) down to $7 \times 10^{-7}$ m (L = 1 m); it was further developed to reduce the calibration repeatability error.

The comparator consists of the body of the machine, a heterodyne laser interferometer for determining the displacement of the microscope carriage, a translating system and a detecting apparatus. Measurement of the displacement of the carriage is realized by laser interferometer that is comprised of Zygo ZMI 2000 laser head and interferometer with the single-pass arrangement. The interferometer provides a resolution of 0,62 nm. Air pressure, temperature, humidity are on line accessed to determine the refraction index of the air by the Edlen formula. The graduation line distances are measured during continuous motion. A moving CCD microscope serves as structure localisation sensor for the measurements of line scales. Before the edge measurements process starts, the microscope objective is positioned in optimum focus by means of a micropositioning mechanism. Average profiles of the graduation lines are formed by summing picture element intensities of each row of the CCD. Line centre is calculated as weighted mean from intensity profile of a line. The edge location is estimated by application of the polynomial fit that allows structure localisation with sub-pixel discernment. Finally, the positions of left and right edge are calculated on the basis of the 50% threshold value of the regression lines, and the centre line position is determined as the arithmetic mean of both edge positions.

The angular control loop - together with the numerical procedure - was applied to compensate and reduce the Abbe uncertainty contribution. The magnification of the NIKON objective lens used was 20× and 50×, and numerical aperture - 0,4 and 0,55 respectively. The microscope on the carriage guided on aerostatic bearings is moved with a controlled velocity of 1 – 10 mm/s.

Extensive experimental examination was 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 interferometre and the measurement point of the microscope may reach 0,662 μm (at calibration speed 3 mm/s), [5]; it can be reduced to 0,016 μm by optimisation the carriage structure and elimination the undesirable modes of vibration.

The calibration experiments were performed that intended to document current capabilities to carry out line scale calibrations on high quality graduated scales made of low thermal expansion substrates. 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, 25 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 substrates.

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. 6 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 3mm/s. The environmental chamber and scale temperatures were held within ±0,05 °C during the measurements.

The positions of the line are corrected for the influence of the temperature deviation from 20 °C and pressure deviations from 1013,25 hPa.

## 4. CONCLUSIONS

Error-related problems specific to a precision line scale calibration in dynamic regime were investigated in this paper. Advanced FE modelling techniques were applied in order to represent the structural behaviour of the measurement carriage system. A new FE model was developed and influences of dynamic processes in the length comparator structure were evaluated.

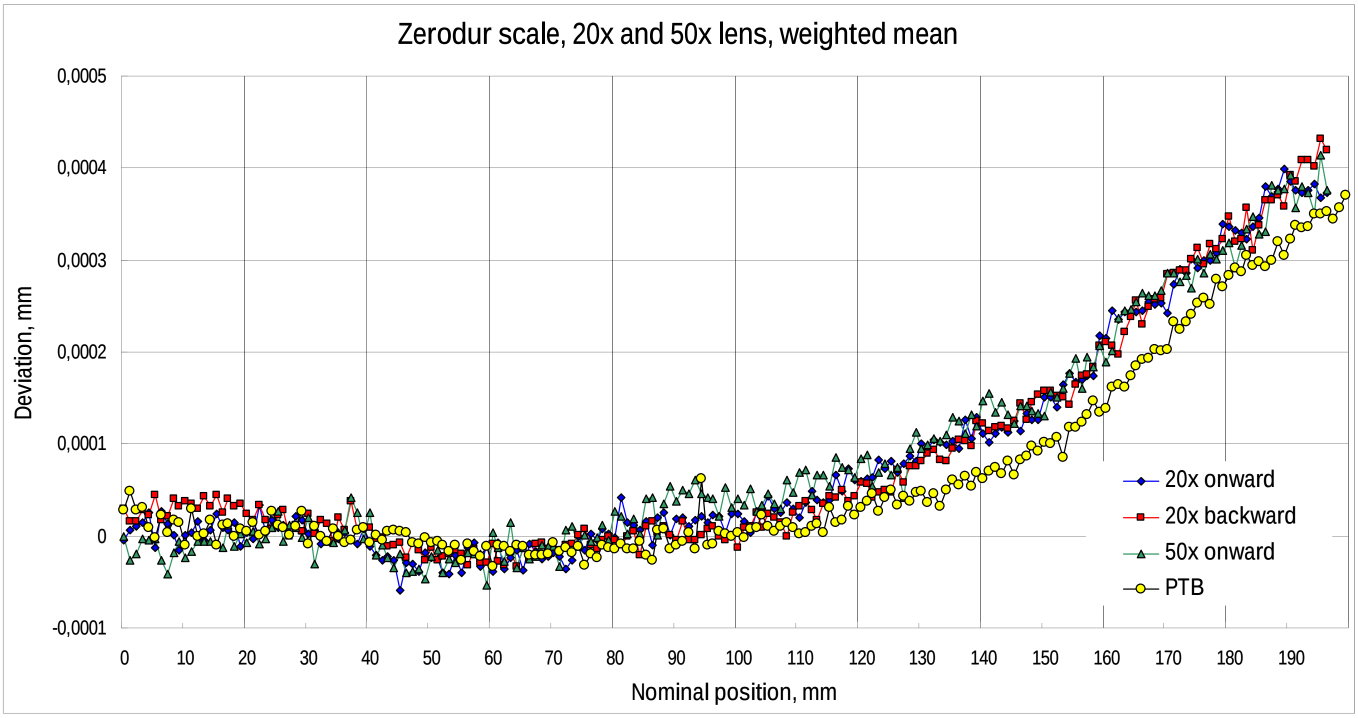

Fig. 6. Calibration results on Zerodur scale, 200 mm graduation, 1 mm step.

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.

Modal analysis performed as well as measurements conducted of the spatial vibrations of comparator revealed that dynamically-induced errors can amount to more than 100 nm at the focal plane and thus noticeably contribute to the measurement uncertainty budget. They can be prominently reduced, in particular, by proper improvement and optimisation of the carriage structure and the carriage drive.

The dynamic calibration error originating due to vibration sources in the structure must be considered and implicated in the uncertainty budget. The analysis performed allows us to evaluate these errors and keep them in control to an adequate level required by the specification for the system.

To investigate the actual measurement performance 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 reached.

## REFERENCES

[1] H. Nakazava, *Principles of Precision Engineering*, Oxford University Press, 1994, 267 p.

[2] J. Flügge, R. Köning, H. Bosse, Recent activities at PTB nanometer comparator, *Proc. SPIE*, "Recent Developments in Traceable Dimensional Measurements", J. E. Decker; N. Brown; Eds. 2003, vol. 5190, pp. 391-399.

[3] S. Kaušinis , A. Jakštas , R. Barauskas, A. Kasparaitis, “Investigation of Dynamic Properties of Line Scale Calibration Systems”, *XVIII IMEKO World Congress*, Rio de Janeiro, Brazil, Sept. 2006.

[4] A. Jakštas, Investigation of Precision Length Calibration Systems. Summary of Doctoral Dissertation, Technological Sciences, Mechanical Engineering, Kaunas University of Technology, Kaunas, Technologija, 2006, 38 p.

[5] S. Kaušinis, A. Barakauskas, R. Barauskas, A. Jakštas, A. Kasparaitis, “Investigation of Vibrations of Line Scale Calibration Systems”, *Journal of Vibroengineering*, , vol. 10, no. 1. pp. 79-89, 2008.

[6] S. Kaušinis, A. Kasparaitis, A. Barakauskas, R. Barauskas, A. Jakštas, A. Kilikevičius, “Line Scale Calibration in Non-Ideal Measurement Situation”, *Solid State Phenomena*, vol. 147-149, pp. 682-685, 2009.