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Dynamic Mode of Line Scale Calibration

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Abstract. The need for high-resolution and high-speed detection of line scale graduations is a result of increasing throughput requirements of precision scale calibration systems. These new demanding requirements can be met by exploiting the advantages of the dynamic mode of calibration. The state-of-the-art platform-based approach to improving calibration systems performance will allow both functional extension to already deployed systems and the design of new ones, capable of adapting to different application patterns and user profiles.

An interferometer-controlled comparator setup has been designed to measure the performance of the dynamic calibration process. A novel 3D finite element model has been developed in order to both investigate thermo-mechanical processes in the comparator structure and evaluate possible temperature influence on geometrical dimensions of the line scale. A series of measurements has been conducted at PTB and MIKES length calibration laboratories in order to evaluate the capabilities of the dynamic calibration of graduated line scales.

Introduction

Current and future applications for line scale calibration systems require much better performance in terms of calibration accuracy and efficiency than those of previously available ones. Satisfying these more demanding requirements ultimately drives demand to tracing/validating the products on their manufacturing line as well as performing a graduation line detection and position measurements in a short time [1].

High-precision measurements of line scales basically apply two main modes of calibration: static and dynamic calibration. Currently static line detection systems are predominantly used in metrology institutes and calibration laboratories worldwide. The static method is potentially more accurate but somewhat slow, whereas the dynamic method offers taking advantages of scale calibration in terms of speed, accuracy and throughput. It also allows construction simplification, because high-precision settling of the moving scale or microscope there is not needed, and the measurement process is less influenced by ambient environmental conditions.

From the other side, the dynamic method encounters difficulties induced by measurement speed fluctuations, time delays, noise and vibrations especially during graduation line detection. Mechanical limitations for dynamic mode are featured by the whole complex mechanical system including error compensation circuits. Error-related problems specific to length measurements are caused primarily by geometrical and thermal deviations of comparator components and the scale. One of the critical points in the dynamic calibration of scales is microscope image acquisition i.e. bringing the specimen into focus before taking an image and measuring any feature. Due to imperfections of the stage i.e. inaccuracy of the motion of the scanning mechanism and vibrations, the microscope slide is not perfectly perpendicular with respect to the optical axis of the imaging system. Measuring even a slightly vibrating structure with any degree of accuracy with an optical microscope is prone to error. Any deviation in the distance of the microscope lens with respect to the scale - for example, when the surface is in motion during data acquisition process - introduces measurement errors. The magnitude of the resulting error can range from a few nm to several μm depending on the magnitude of such disturbances and the measurement setup. The most common error associated with small vibrations is error in detection of the line scale graduation.

Despite dynamics-induced disturbances, available modern technologies enable precision line/edge detection in dynamic mode of measurement with a speed up to 20 mm/s. Such systems with photoelectric slit microscopes are used in comparators designed by German National Metrology Institute (PTB) and Japanese company Mitutoyo. They allow for line scale calibration with measurement uncertainty less than 40 nm/m, and ensure graduation line detection repeatability of 5 nm, [1].

The latest generation of machine vision systems also features major improvements over earlier designs. New tools such as fast digital cameras, new illumination systems as well as new image scanning and processing technologies and standards allow for high-speed imaging of from 250 frames per second (FPS), higher data transfer rates and permit much greater scanning speeds in low light. With faster processors, modern systems can both acquire more information from cameras at faster frame rates and take advantage of more complex line/edge detection algorithms. This makes it possible to build a high-speed image capture and analysis system to meet particular needs of dynamic calibration of precision line scale.

An example of this attitude is the line scale comparator with moving CCD microscope at Finnish Centre for Metrology and Accreditation (MIKES). Having a comparatively simple design, the MIKES' comparator displays the uncertainty of calibration that is very similar to that of systems with slit microscopes, albeit the calibration process is slower, [2-4].

The paper describes recent joint work performed at Kaunas University of Technology and Brown & Sharpe-Precizika in precision length metrology aimed at the development of an interferential comparator with moving microscope for line scale calibration up to 3.5 m length. The research has been focused on the dynamic mode of calibration and simultaneous evaluation of the influence of dynamic and thermal factors upon the inaccuracies of measurement. A precision interferometer-controlled setup with NIKON modular CMOS microscope has been designed in order to carry out the experiments. Some measurements on dynamic calibration of the line scale were conducted at PTB and MIKES.

Modeling of Influence of External Factors

The finite element (FE) method has been recognized as an advanced modeling tool able to represent the structural behavior of the system by ensuring a very high level of adequacy of the model to reality, [5]. The state-of-the-art FE technique has been applied in order to evaluate the possible influence of dynamic and thermal factors upon the inaccuracies of measurement. Two basic physical phenomena are of interest:

1. Displacements of the structure as a consequence of applied dynamic excitations, as well as, non-homogeneities of the temperature field;
2. Heat transfer inside of the structure caused by an external temperature field.

All necessary aspects of the dynamic behavior of the comparator can be investigated by employing small displacement elastic structural models as

$$[\mathbf{M}]\{\ddot{\mathbf{U}}\}+[\mathbf{C}]\{\dot{\mathbf{U}}\}+[\mathbf{K}]\{\mathbf{U}\}=\{\mathbf{F}(t)\}+\{\mathbf{Q}(t)\} \quad , \tag{1}$$

where $[\mathbf{K}],[\mathbf{M}],[\mathbf{C}]$ are stiffness, mass and damping matrices of the structure, $\{\mathbf{F}\}$ is nodal vector of external excitation forces, $\{\mathbf{Q}\}$ is nodal force vector caused by the temperature propagation effect.

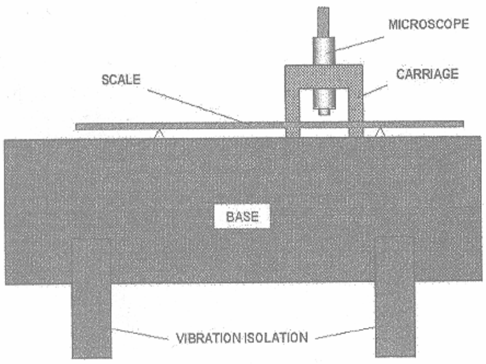


Fig. 1. Mechanical layout of comparator

The mechanical layout of the comparator is depicted in Fig. 1. FE models enable us to simulate all 3D displacement or vibration patterns of the structure. Vertical vibrations of the microscope may lead to defocusing. Vibrations in the direction of motion may cause detection errors in determining positions of graduation lines.

In practice the excitation vectors $\{\mathbf{F}\}$ caused by external dynamic effects or by moving parts of the structure are not known explicitly. A spectrum analysis is one in which results of a modal analysis are used with a known spectrum to calculate displacements and stresses in the structure modeled.

The influence of temperature is another accuracy-limiting factor in the length metrology. For high precision calibration systems, it is essential to evaluate an average volume temperature of some parts of a mechanical comparator as well as the temperature of the scale.

Vector $\{\mathbf{Q}\}$ in equation (1) can be easily determined if the temperature field inside of the structure is known. If only the surrounding transient temperature field is known, temperatures inside of the structure can be obtained by solving the thermal conductivity problem

$$[\mathbf{C}_{th}]\{\dot{\mathbf{T}}\}+[\mathbf{K}_{th}]\{\mathbf{T}\}=\{\mathbf{S}_{\infty}\} \quad , \qquad (2)$$

where $[\mathbf{C}_{th}],[\mathbf{K}_{th}]$ are thermal capacity and conductivity matrices of the structure, $\{\mathbf{S}_{\infty}\}$ is nodal vector of heat sources determined by heat convection across the surface of the structure.

Under real calibration conditions, temperature measurement is possible only at certain points. The response time of temperature sensors is also rather long (from several seconds to several minutes). Therefore, fast temperature changes cannot be detected and consequently, the measurement uncertainty increases, [6]. This factor becomes very important while calibrating long scales. Because of high requirements for geometrical stability of calibration system, temperature deformations induced by changes of some hundredth parts of Kelvin must be considered.

A 3D FE model has been developed in ANSYS in order to investigate thermo-mechanical processes in the comparator structure and evaluate possible temperature influence on geometrical dimensions of the line scale. The impact of temperature on mechanical deformation of the line scale can be simulated in several ways:

- Temperature values at certain points of the construction can be detected experimentally and used for calculation;
- Temperature field can be calculated depending on the assigned non-homogeneity of the environment temperature by taking into account heat convection processes between parts of the structure and its surrounding (Fig. 2).

The model is capable of predicting the system's behavior under thermal load and enables us to investigate the thermo-mechanical processes in the system, by taking into account both static and dynamic disturbances and parameter deviations.

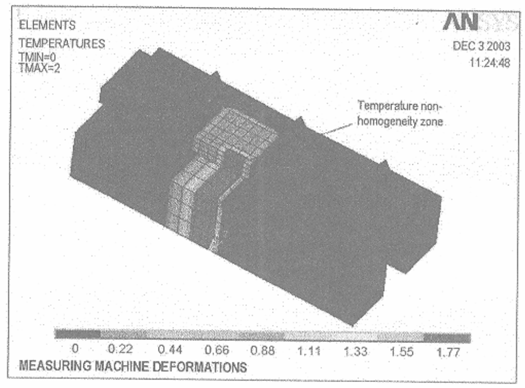
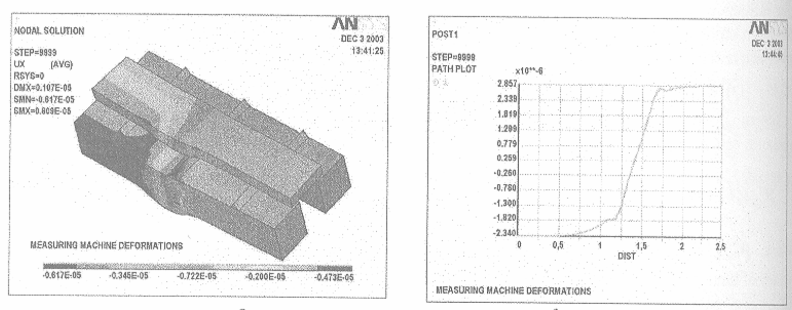


Fig. 2. Thermal load for line scale comparator model

Fig. 3 depicts the contours of the strain field in the structure and displacements of the midline of the line scale conditioned by the temperature non-homogeneity presented in Fig. 2.



a b

Fig. 3. Deformations of line scale model due to non-homogeneity of ambient environment temperature: *a* – image of strained construction; *b*- deformations of midline along line scale.

Experimental Examination of the Dynamic Calibration Process

As the dynamic calibration process is to be examined in real time, experiments of the line scale calibration with both a slit and moving CCD microscope have been carried out in specific operating modes, and dependence of the accuracy of dynamic calibration vs. speed has been studied.

For precise and full-scale evaluation of the application of dynamic mode of the line scale calibration a CMOS-microscope based edge detection system has been developed, [7]. The system uses a modular focusing unit to capture image data and incorporates a set of high-quality objectives and image-processing software. Good quality images of precision graduation structures have been obtained, and average profiles of graduation lines have been examined.

A series of measurements has been conducted at MIKES length calibration laboratory in order to investigate dynamic calibration capabilities of graduated line scales. The comparator setup with a moving microscope and electrically shuttered CCD camera was used for detection of the scale graduation position, [3]. The microscope and the CCD camera are mounted on a carriage, and the microscope is adjusted perpendicular to scale plane within 0.2°. The microscope carriage is pulled by a DC motor along the stone rail on the air bed. The line scale has been aligned under the microscope to a position at which the appropriate graduation lines were in focus. The position of the microscope has been measured by laser interferometer placed on a vibration-isolated stone table.
Measurements were performed with calibration speeds in ranges from 0, 15 mm/s up to 0, 35 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 data was collected when the microscope carriage was moving. The averaged positions of graduation lines measured, L_a, at different speeds are shown in Fig 5. It is clearly seen that speed variations have no perceptible influence on measurement results. Higher measurement speed was mainly limited by the design of the carriage drive.
Repeatability errors of graduation line detection with different measurement speeds are presented in Fig. 6. Experiments have shown that given the speed of the microscope carriage does not exceed 0, 35 mm/s, the accuracy of line detection falls into interval of 20-60 nm.

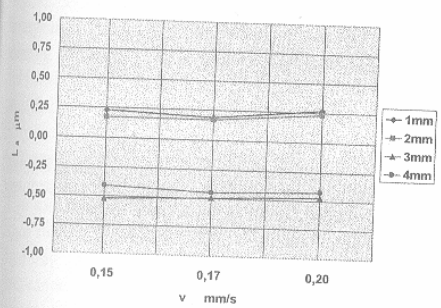


Fig. 5. Average graduation line position L_a measured with moving microscope at different measurement speeds

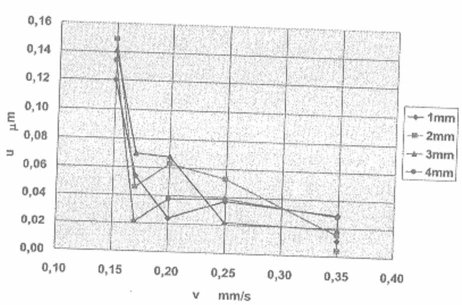


Fig 6. Measurement uncertainty u (95%) of graduation line detection for different speed of microscope carriage

A precision line scale comparator equipped with a slit microscope and laser distance sensors was used for investigation of graduation line detection in dynamic mode at the PTB Length and Angle Graduations Department [1]. The reflected light from the scale after the slit is detected by photomultiplier and measured by A/D converter simultaneously to the laser interferometer readings. Laser distance sensors are designed to keep microscope in focus. The line scale adjusted on the precision carriage was moved with shifting velocities. The repeatability of three consecutive measurements of the scale at certain speed is shown in Fig. 7 as the deviation from the mean of these measurements. The measurement results obtained with this setup reveal quite similar accuracy characteristics in terms of repeatability (see Fig. 7) compared with data gathered from calibration system with moving CCD microscope. The measured performance confirms that the investigated measurement system operates reliably at velocities up to 15-25 mm/s. Whenever the measurement system is not able to count fast enough, measurement error from period to period becomes larger. Owing to experiments carried out it has been concluded that the measurement speed up to 20 mm/s and more could be reached without appreciable loss in measurement accuracy.
The influence of geometrical errors on performance of the measurement system and its nonlinearities can be determined by the arrangement of the scanning system.

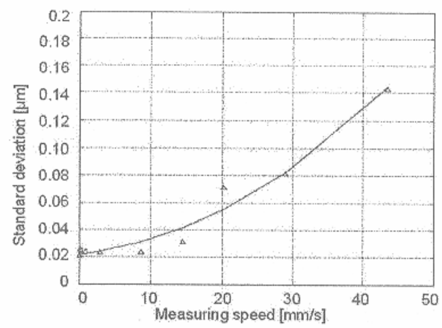


Fig. 7. Line position deviation vs. speed measured with photoelectric slit microscope

Conclusion

The need to perform measurements in a short time is a result of increasing throughput requirements of line scale calibration systems.
Taking advantages of modern slit microscopes and CCD/CMOS-based technical vision systems as well as faster processors' and more complex data processing algorithms' one leads to greater improvement of dynamic characteristics of length calibration systems.
Advanced modeling methods and tools enable us to represent the structural behavior of the calibration system and ensure a high level of adequacy of model to the reality.
The measured performance confirms that dynamic calibration mode permits precision line detection at much greater than conventional scanning speeds without appreciable loss in measurement accuracy.

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