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Line Scale Calibration in Non-Ideal Measurement Situation

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Abstract. The precision line scale calibration in dynamical mode of operation is considered. A new interferometer-controlled comparator with moving microscope has been developed and optimised in order to reduce both the measurement uncertainty and calibration process duration.
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. They can be prominently reduced, in particular, by proper improvement and optimisation of the carriage structure and elimination of the dry friction in the carriage drive.

Introduction

One of the most sophisticated challenges for science and the high technologies engineering is the growing need to address real industrial problems and embed the traceable length metrology directly into technological processes by performing precise dynamic measurements in more demanding environments than those of calibration laboratories, [1]. The relevance and necessity of tackling the problem of precision and high-speed line scale calibration is primarily driven by the rapid increase of demands on calibration efficiency of precision scales. Considerably higher precision and efficiency requirements are set for the new systems. The calibration is aimed at the traceability of precision line scale parameters during manufacturing process, in the technological line, and the measurement procedure should be as short as possible.

In this paper, we will describe the key points of the current design of an interferometer-controlled measurement machine dedicated to the one dimensional calibrations of line scales and linear encoders, [2, 3], as well as the measures taken to reduce the uncertainty contributions in non-ideal measurement situation.

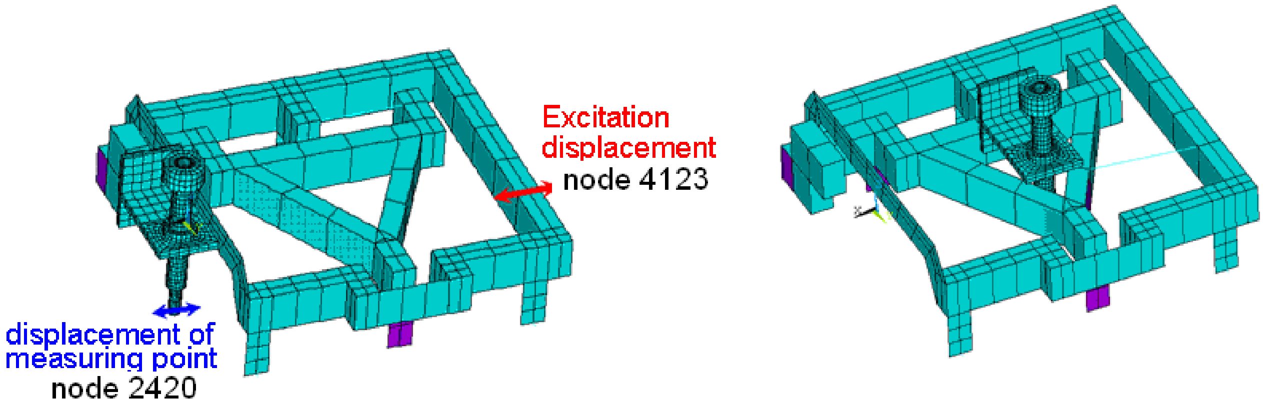
The comparator is developed to calibrate line graduation scales and incremental linear encoders. It consists of the body of the machine, a heterodine laser interferometer, a translating system and a detecting apparatus. A moving CCD microscope serves as structure localisation sensor for the measurements 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 comparator has already proven its performance during the measurements of line scale. It will be still developed and optimized to reduce both the calibration uncertainty and calibration process duration.

Finite element 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, [4]. 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 should be optimised and drive-originated vibrations reduced.

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 are presented in Fig 1.



(a) (b)

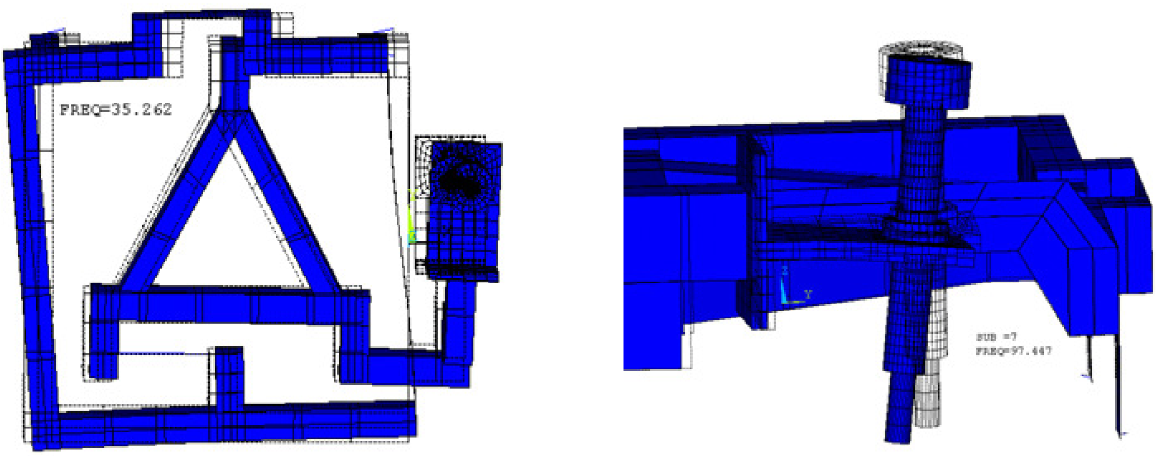
Fig. 1 Two finite element models of the microscope carriage
a) - initial (non-optimized scheme); b) - optimized scheme

The vibrations of the carriage 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 structure. Three main reasons preconditioned by the construction features of the carriage, which cause transient vibrations in the frequency range up to 100 Hz have been identified, Fig. 2 and Fig. 3:

- the elasticity of the aeroelastic bearings;
- the shear elasticity of the master frame, which causes considerable amplitudes at frequencies close to 35 Hz (vibration mode in Fig. 2a);
- the elasticity of the support of the microscope, the construction of which is similar to a cantilever attached to the slave frame (vibration mode in Fig. 2b).

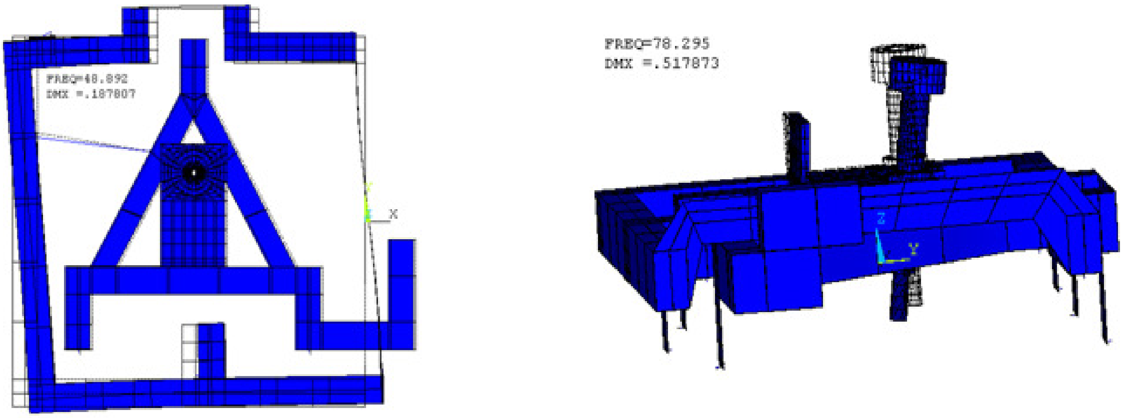
The transient vibration of the measuring point of the microscope due to excitation of the start-stop movement of the carriage drive is presented in Fig. 4a. Given the input pulse of the 200 ms duration the amplitude of undesirable vibrations may amount to 0,15 – 0,20 of the displacement amplitude.

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, two modes of which are presented in Fig. 4. As it can be clearly seen from comparison of the measurement data presented in Fig. 5a and Fig. 5b, the reduction of vibrations caused by the carriage drive can be substantial.



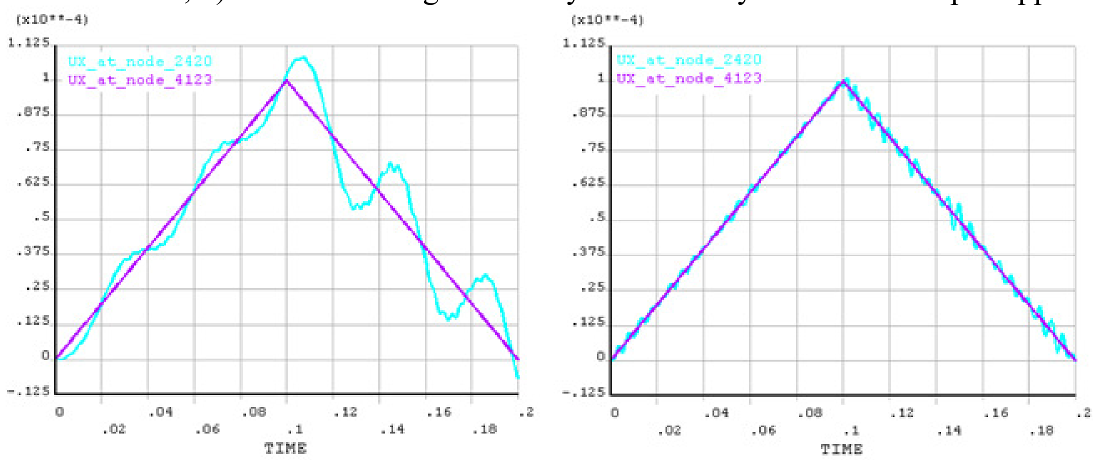
(a) (b)

Fig. 2. Two important modes of vibration of the structure shown in Fig. 1a:
a) 35.3 Hz mode governed by shear elasticity of the master frame and elasticity of aeroelastic bearings of the slave frame; b) 97.4 Hz mode governed by the elasticity of he microscope support.



(a) (b)

Fig. 3. Two modes of vibration of the optimized structure shown in Fig. 1b:
a) 48.9 Hz mode governed by shear elasticity of the master frame; very small amplitudes of the slave frame; b) 78.3 Hz mode governed by the elasticity of he microscope support

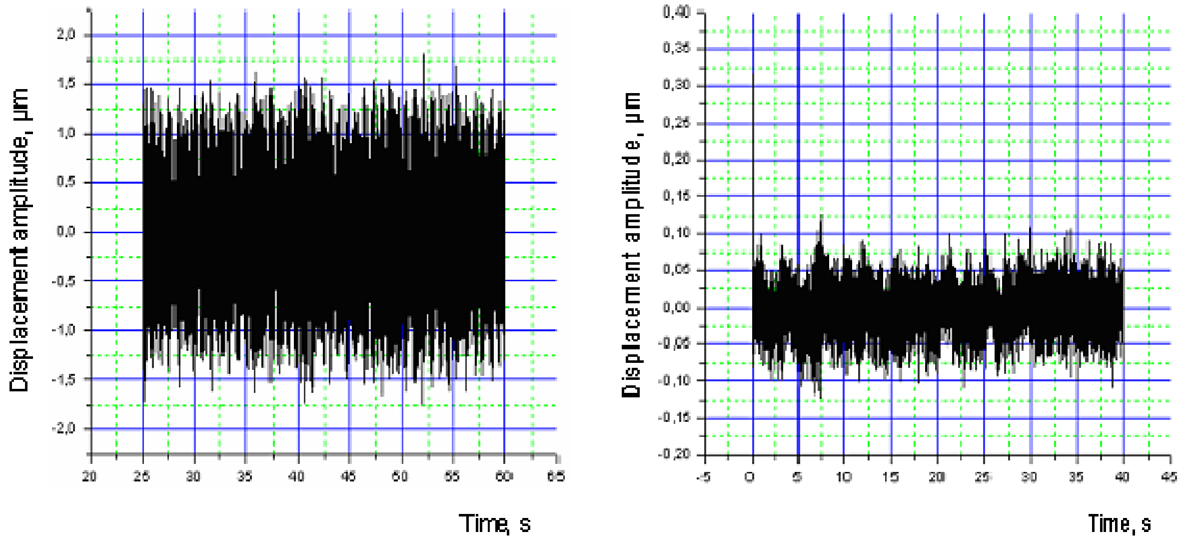


(a) (b)

Fig. 4. The responses of the structures shown in Fig. 1a and 1b to the displacement pulse generated by the drive; a) structure in Fig. 1a; b) structure in Fig. 1b

Experimental investigation

The precision measurements have been conducted in order to evaluate the impact of small vibration on performance of the line scale calibration process. The experimental results revealed that the standard deviation of the relative deviations of the measurement mirror caused by operation of the carriage drive may reach 0,662 µm; they can be reduced to 0,041 µm by eliminating the dry friction in the drive, Fig. 5.



(a) (b)

Fig. 5. Relative vibrations of the measurement mirror with respect to the line detection microscope: a) – induced by the presence of dry friction in the carriage drive at the calibration speed 3 mm/s, b) – without dry friction in the carriage drive

Conclusions

The dynamic calibration error originating due to vibration sources should be considered and implicated in the uncertainty budget while embedding the traceable length metrology directly into technological processes.

The dynamic behaviour of the line scale comparator carriage has been investigated by both finite element modelling and experimentally. Computational analysis enabled to ascertain 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.

The measured performances have confirmed that after performing an optimisation the investigated measurement system can operate reliable at velocities up to 8 mm/s without appreciable loss in measurement accuracy.

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