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Dynamic error reduction of a nanometre-accurate Abbe-compliant position measurement system

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Abstract
Ultra-precision machine tools can be brought to higher accuracies by fully exploiting precision engineering design principles. For that reason, a linear encoder-based measurement system called 'moving-scale' has been developed, compliant with the Abbe-principle and allowing functional separation of the metrology and structural loop. Previous work showed that the thermo-mechanical stability of a 1-DOF system with a measurement length of 120 mm was 18 nm for temperature changes of ±0.5 °C. This paper describes the characterisation of the dynamic errors occurring during measurement of the position of a moving target surface. The largest error sources have been identified and reduced and were experimentally verified in a dedicated setup where the moving-scale position measurement was compared to that of a stable reference. The measurement uncertainty related to these dynamic errors has been shown to be 5 nm, which brings the total measurement uncertainty of the 1-DOF moving-scale measurement system to 21 nm.

Machine tool, Ultra-precision, Metrology, Encoder, Dynamic error

1. Introduction

Increasing machine tool accuracy has always been one of the main drivers of technological evolution. State-of-the-art ultra-precision machine tools rely on accurate guiding systems such as air bearings or hydrostatic bearings, millikelvin temperature control and linear position measurement systems with sub-nanometre resolution such as linear encoders or laser interferometers. An elaborate application of certain precision engineering design principles such as the Abbe or Bryan measurement principle and functional separation of the structural and metrology loops, could even further improve the accuracies of ultra-precision machine tools, because they reduce the two most significant machining errors: thermo-mechanical and geometrical errors.

Therefore, KU Leuven has proposed a new measurement configuration based on linear encoders that enables three-degrees-of-freedom (DOF) measurement according to the Abbe or Bryan principle to reduce the geometrical errors and that allows integration of metrology frames for reduction of the thermo-mechanical errors [1-2]. The so-called 'moving-scale system' tracks the movement of a planar target surface attached to the stage of which the position needs to be measured only in the direction of measurement, but allows translation of the target surface perpendicular to the measurement direction. The position measurement of the target surface consists of a combination of the long-stroke linear encoder measurement and the short-stroke measurement of a capacitive sensor that is placed in line with the linear encoder. The system can be arranged in a configuration which allows the scales to always be directed to the centre of the tool, in this way eliminating the Abbe offset in machine tools and drastically improving the position measurement accuracy. The moving-scale system has been designed for high thermo-mechanical stability and the error budget for the system indicates that a measurement uncertainty of 21 nm for a measurement length of 120 mm is within reach [3]. The uncertainty caused by thermo-mechanical errors has been experimentally verified to be 18 nm for temperature changes of ±0.5 °C [4].

In machine tool applications, the dynamic performance of the metrology system during motion of the slides is of high importance, since dynamic errors are directly copied into the workpiece. Therefore, this paper focuses on the dynamic errors of the moving-scale measurement system. Section 2 describes the layout of the setup used for assessment of the errors and the measurement procedure involved. The next section describes the largest error sources and how they were reduced. Finally, experimental results show the performance of the moving-scale measurement system during tracking of a target surface.

2. One-DOF test setup for moving-scale measurement system

2.1. Layout of the setup

The working principle of the moving-scale measurement system has been explained in [3]. In Figure 1, a dedicated setup for determining the performance of the measurement system is depicted. In this setup, the moving-scale (MS) tracks the movement of a reference-scale (RS) that moves in the same direction while the position of this reference system is compared to the measurement of the moving-scale. A difference in measured position is defined as a measurement error. The reference-scale should however not be calibrated to the absolute length standard because only the repeatability of the moving-scale will be determined. Systematic errors are repeatable and are removed from the measurements. The setup has been designed in such a way that a uniform thermal expansion of the metrology frame can be compensated by using two reading heads on the Zerodur® scale of the reference-scale system. Attention has been given to kinematic thermo-mechanical stable mounting of the components in both the moving-scale and reference-scale system, and the mounting of the reading heads of the encoders. Both scales and the capacitive sensor are in line to eliminate the Abbe offset. This allows the use of mechanical roller bearings for the guiding of both systems.

2.2. Measurement procedure

The measurement error of the setup is defined by the following equation:

$$e = x_{RH2} - x_{RH1} + \Delta x_{cap} + \frac{L_1}{L_2}\left(x_{RH2} - x_{RH3}\right),$$

in which x_{RH1}, x_{RH2} and x_{RH3} are the positions indicated by the moving-scale reading head and the two reference-scale reading heads respectively, Δx_{cap} is the displacement measured by the capacitive sensor and L_1 and L_2 are the distances between the reading heads. The reference-scale is traversed over its measurement length and the measurement error is calculated. Because the scales have non-linearities dependent on the measured position up to a few hundred nanometres, the calculated measurement error also shows these errors. They are however repeatable and are subtracted from the measurement. What remains are the non-repeatable measurement errors, for instance caused by sensor noise, system dynamics and non-repeatable Abbe errors.

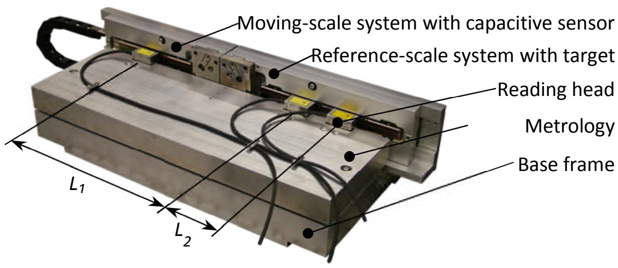

Figure 1. Layout of the setup for determining the reproducibility, repeatability and dynamic stability of the One-DOF moving-scale measurement system.

3. Repeatability and dynamic errors

3.1. Reduction of the largest dynamic error sources

The largest dynamic errors were caused by non-linearities of the capacitive sensor and vibrations due to stick-slip in the guides. The non-linearities of the capacitive sensor were calibrated by comparison with the measurement of the scale, which is in-line with the capacitive sensor. The vibrations caused by stick-slip in the guides were reduced by replacing the previously used recirculating ball bearings by roller bearings which exhibit a much smoother motion. It had been identified that the stick-slip effect excited the eigenfrequencies of the guide, which resulted in high-frequency accelerations. These accelerations caused movement of the kinematically connected scale and capacitive sensor relative to each other, resulting in a measurement error that has been simulated and later experimentally verified to be 20 nm/(m/s^2) (Figure 2).

3.2. Experimental results

After reduction of the above described dynamic errors, experiments have been carried out to verify the non-repeatable error. In these experiments, the moving-scale system actively tracked the position of the reference-scale system by controlling its linear motor in such a way that the gap measured by the capacitive sensor stayed within the sensor's measurement range. The results are shown in Figure 3. The graph shows slowly varying errors and errors at higher frequencies. The errors at higher frequencies are due to instability of the control loop due to non-linear behaviour of the current amplifier in the linear motor driver. Other high-frequency errors were related mostly to sensor-noise. The low-frequency errors can be ascribed to residual non-repeatable Abbe-errors and to non-perpendicularity of the capacitive sensor to its target surface together with small angular error motions of the guides. The measurement uncertainty (k=2) has been calculated based on these results, which was found to be 5 nm.

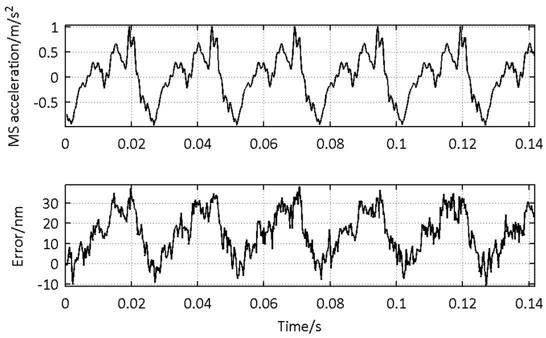

Figure 2. Acceleration dependent error of the moving-scale measurement system.

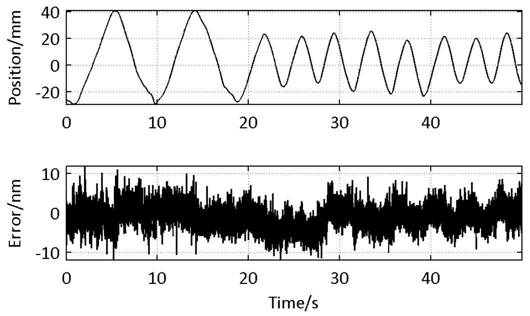

Figure 3. Measurement errors of the moving-scale measurement system during tracking of the position of a moving target surface (resulting uncertainty: 5 nm).

4. Conclusion and future work

This paper described the experiments carried out to characterise the dynamic errors and related measurement uncertainty of a measurement system based on linear encoders that allows measurement according to the Abbe-principle in three DOF. The largest dynamic errors have been reduced and it has been experimentally verified that the measurement uncertainty associated with dynamic errors is 5 nm. Including this uncertainty in the error budget of the measurement system indicates that a measurement uncertainty of 21 nm can be reached. In future work, a 3-DOF system will be developed to verify the 3D measurement uncertainty of the system.

5. Acknowledgements

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