Determining the random measurement errors of a novel moving-scale measurement system with nanometre uncertainty

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Abstract

This paper describes a setup with a low sensitivity to temperature variations for determining the random measurement errors of a measurement system applying a moving scale. This moving-scale system is developed for advanced equipment such as ultra-precision machine tools and should operate with a measurement uncertainty of 15 nm for a measurement length of 109 mm and temperature variations of 1°C. Temperature drift is identified as the most contributing source of errors and therefore should be accurately determined. A dedicated setup has been designed for this task.

1 Introduction

1.1 Measurement system with moving-scale

Measuring displacement of the stages in ultra-precision machines is mostly done by linear encoders or laser interferometers. Linear encoders can generally not be configured like laser interferometers in an arrangement such that Abbe-offset is eliminated for a multi-DOF system, but they outperform laser interferometers in terms of stability w.r.t. environmental changes [1]. Earlier work at KU Leuven has proposed a moving-scale measurement system in a configuration compliant with the Abbe principle [2]. A prototype has been designed and experiments have been conducted on critical components. Previous research has indicated it is possible to reach a 15-nm measurement uncertainty of a 1-DOF moving scale measurement system with a measuring length of 109mm [3].

1.2 Error budget and scope of paper

The error budget for the 109-mm moving scale measurement system is shown in Table 1. The measurement uncertainty consists of random and systematic measurement errors. Systematic errors, such as scale errors and Abbe errors resulting from repeatable error motion of the guides, will be determined and eliminated in the future by calibration with a laser interferometer. To determine the random errors however, laser interferometry is not convenient since it would require extremely stable ambient conditions or even a vacuum along the measurement path of the laser. Therefore, the random errors, including quasi-static temperature drift, are determined in a separate setup. This paper describes the design of this setup and discusses the results of some preliminary experiments.

Table 1: Error budget of 109-mm moving-scale measurement system.

Component	**Value [nm]**
Random measurement errors (±2σ)	**8**
Temperature drift reading head	5
Difference in drift between capacitive sensor and weather station	5
Other temperature errors (scale expansion, scale carrier expansion, ...)	3
Difference in humidity drift between cap. sensor and weather station	2
Dynamic errors	3
Systematic measurement errors (±2σ)	**13**
Abbe error	5
Other Geometric errors (Cosine error, ...)	3
Linear scale calibration error (estimation)	10
Other measurement errors (non-linearity, ...)	5
Total (±2σ)	**15**

2 Measurement setup for random errors

2.1 Design concept

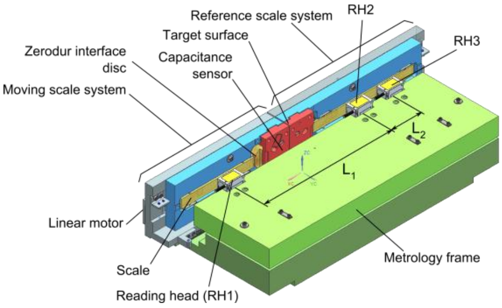


Figure 1: Measurement setup for random errors

Figure 1 shows the layout of the setup. It consists of a moving-scale measurement system with a linear scale and a capacitive sensor located on a scale carrier. The scale carrier is driven by a linear motor. The capacitive sensor measures the displacement of a target surface on another linear-motor-driven slide. The first linear motor is controlled in such a way that the gap measured by the capacitive sensor remains constant. The displacement of the target surface is calculated based on the readings of the linear encoder and the capacitive sensor on the moving-scale measurement system. In order to compare the measured values, the position of the target surface is simultaneously monitored by a linear encoder that is located on a separate scale carrier containing the target surface and is in line with the first scale. This second linear encoder gives the true displacement of the target surface and this is used to compare with the measured value of the moving-scale measurement system.

Two Zerodur® interface discs provide a thermal fixed point at the front surface of the capacitive sensor for the moving linear scale and at the target surface for the reference scale. Consequently, the virtual distance between a point on the moving scale and a point on the reference scale should not vary with temperature changes.

The position of the linear scales is measured using three reading heads RH1, RH2 and RH3. The reading heads are fixed to an aluminium metrology frame. Because the reference scale is made out of Zerodur®, which has a near-zero coefficient of thermal expansion, the measured displacement between the two reference scale reading heads equals the thermal expansion of the metrology frame. Thereby we assume that the thermal expansion is uniform in the measurement direction.

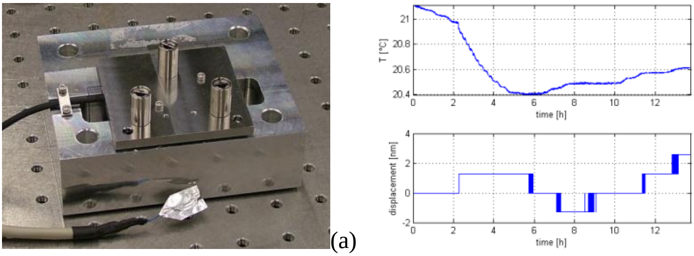
The random measurement errors indicated in Table 1 are equal to

$$e_{random} = (I_{RH1} + I_{cap}) - I_{RH2} + \frac{L_1}{L_2}(I_{RH3} - I_{RH2}).$$

There will be a significant contribution of the random errors of the reference scale system included in these measurements since they consist of the same error components as the moving scale system, but without the drift of the capacitive sensor. The random errors of the reference scale system will amount to 6 nm, bringing the total random measurement errors to 10 nm (±2σ).

2.2 Preliminary experiments

An important part of the thermal stability is attained by proper mounting of the reading head, a Heidenhain LIP28R. Therefore, the reading head is bolted to a carrier made of the same material as the case of the reading head. This carrier is then kinematically mounted to the metrology frame by three ball-in-V mounts. The point where the lines through the V-grooves intersect is the thermal centre, which is at the same position along the measurement direction as the thermal centre of the internal grating of the reading head. In this way, the measurement drift of the reading head will only be dependent on the expansion of the metrology frame and not on the expansion of the reading head itself. To check the position of this thermal centre, a setup has been built up and experiments have been carried out. Figure 2 shows the setup and the drift of the reading head with changing temperature. Since the thermal centres of reading head and scale coincide in this setup, there is negligible temperature dependent drift.



(a) (b)

Figure 2: Setup for verification of thermal centre (a) and measurement results (b)

3 Conclusion

The design and preliminary experiments on critical components of a measurement setup for random errors in a moving-scale measurement system are presented. The setup, which is currently being manufactured, shall verify if the random errors will not exceed 10 nm (±2σ). Experiments have verified that the temperature drift is negligible once the thermal centre of the reading head is properly defined.

4 Acknowledgements

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