Design of a precision measurement system using moving linear scales

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Abstract

A new measurement concept in a configuration conform to the Abbe principle and using moving linear scales instead of interferometers is proposed here. The paper describes the details of the design of a 1-DoF prototype setup based on this concept. An error budget calculation estimates that the measurement uncertainty can be as low as 15 nm. Solutions are presented for reducing the effects of the largest uncertainty contributions, namely the temperature and humidity drift of the capacitance sensor and the temperature drift of the reading head of the linear scale.

1 Design of measurement system with moving scales

Measuring displacement compliant with the Abbe principle is one of the key methods to increase accuracy in high-precision machines [1]. According to this principle, linear errors, due to rotational displacements by guide errors, flexibility in bearings or thermal expansion of the machine components can be immediately corrected for when measuring in-line with the functional point. In a multi-degree-of-freedom configuration, this principle often requires a measurement system being able to measure the displacement of a surface moving perpendicularly to the measurement direction. Laser interferometers are mostly used in such an arrangement, but they suffer from environmental changes; Linear scales, on the other hand, are highly stable w.r.t. temperature, humidity and ambient pressure changes, but traditionally can only be used in a stacked configuration of slides.

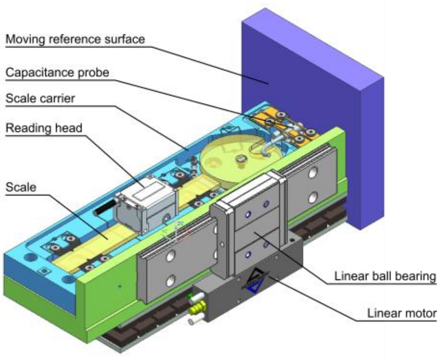

Figure 1: Test setup of the moving scale measurement system

KULeuven has proposed a new concept for measuring in an Abbe-compliant configuration using moving linear scales [2]. The design of a 1-DoF prototype setup based on this concept is shown in Figure 1. This system consists of a Zerodur® scale with a measuring length of 120mm (Heidenhain LIP281, 1nm resolution) and a capacitance sensor (Lion Precision, 2nm resolution) in line with the measurement direction of the scale. Both scale and capacitance sensor are mounted on a scale carrier supported by linear ball bearings and are driven by a linear motor. The capacitance sensor serves as a non-contact displacement sensor between the moving reference surface and the scale carrier. The linear motor is controlled in such a way that the gap measured by the capacitance sensor remains constant. The drift of the capacitance sensor is compensated by a separate weather station sensor mounted in the same way and pointed to a fixed reference surface. Thermal expansion of the scale carrier is cancelled out through kinematic design, whereby the scale carrier expands w.r.t the Zerodur® scale around a thermal centre at the probe tip. An error budget has been made (Table 1), indicating the measurement system can measure the movement of the reference surface with an uncertainty of 15 nm (k=3) in an environment with temperature control within ±0.5 °C.

2 Improving stability w.r.t. environmental changes

2.1 Compensation of capacitance sensor drift

The mounting of capacitance sensors is schematically shown in Figure 2. For the sensor on the moving scale system, the reference surface is that of the measured slide. The sensor is kinematically constrained by supporting it on four precision balls of which the two rear-end balls are supported on a leaf-spring structure that allows expansion of the probe to the back. Consequently, thermal drift is only caused by an expansion difference between probe and block over a distance L. By using the same material for the probe mount on the moving scale system and the weather station, this expansion, together with other corresponding drift errors such as humidity drift and temperature drift of the electronics, can be

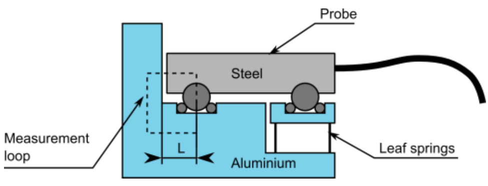

Figure 2: Capacitance probe mounting in weather station.

compensated. This concept has been experimentally investigated by comparing the drift of two probes located in two weather stations that were subjected to the same environmental changes. Figure 3 shows the drift is only 5 nm for a temperature change of 0.9°C and 1% relative humidity change (averaged) and is probably due to a slight difference in sensitivity of the sensors to humidity changes.

Table 1: Error budget of the moving scale measurement system.

Component	**Value [nm]**
Temperature drift reading head	5
Difference in drift between capacitance 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
Abbe error	5
Other Geometric errors	3
Dynamic errors	3
Linear scale calibration error (estimation)	10
Other measurement errors (non-linearity, noise, calibration,...)	5
Total (k=3)	**15**

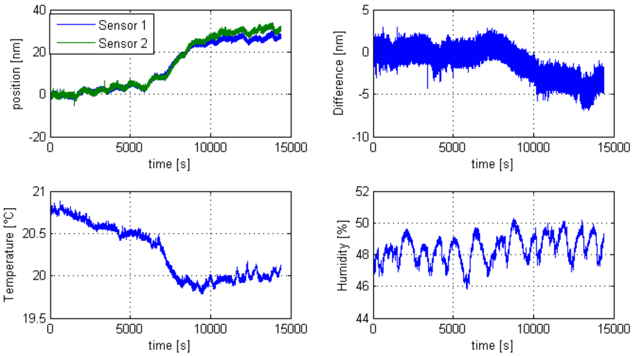

Figure 3: Drift comparison between two capacitance sensor weather stations.

2.2 Reading head temperature stability

The Heidenhain LIP28R reading head is made of steel and its measurement point is not located at the reading head centre. Therefore, a uniform expansion of the reading head can still cause a measurement drift. By mounting it on an aluminium interface with a leaf spring structure, the thermal centre between reading head and interface can be located at the measurement point (Figure 4). This interface can then be mounted on an invar or Zerodur® metrology frame with another leaf spring structure providing a thermal centre. The leaf spring structure can also be embedded in the metrology frame itself. This mounting method has been experimentally investigated. Figure 5 shows a drift of 25 nm for a temperature change of 1°C. Further research is now focusing on a new mounting concept that it is expected to reach a stability of 5nm.

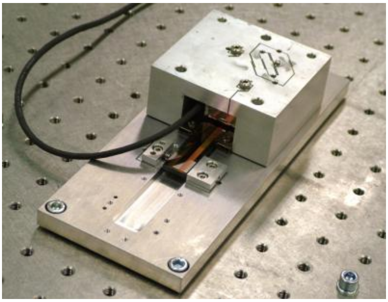

Figure 4: Reading head stability setup

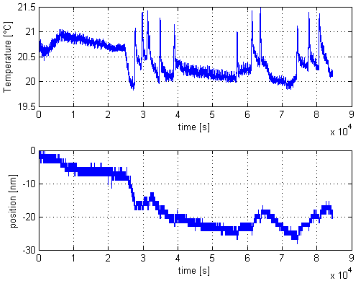

Figure 5: Reading head stability results

3 Conclusion

The design and experiments of a 1-DoF measurement system using moving linear scales have been carried out. By using a capacitance sensor acting as a weather station, the most important environmental drift could be eliminated. Thermal drift of the reading head is compensated by applying a thermal centre. The total measurement uncertainty of the system is about 15 nm (k=3). Future research should improve this concept.

4 Acknowledgement

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