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Straightness measurements with sub-nanometre repeatability

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Abstract
We report on results of straightness measurements of a graduated scale using the Traceable Multi-Sensor method. For this purpose, a sensor element consisting of three heterodyne interferometers was integrated at PTB's length reference comparator. For a scale with a grating of 322 mm length a repeatability below 0.1 nm and an uncertainty below 1.5 nm was achieved.

Keywords: Straightness measurement, error separation, interferometry

1. Introduction

The Nanometer Comparator (NMC) was upgraded for an additional straightness measurement capability to calibrate position and straightness deviations of suitable encoder systems and of aligned structures on photomasks with uncertainties in the single-digit nanometre regime [1]. Straightness references in embodiment of a straightedge or a measurement system are used for a fast and repeatable positioning to improve the quality of fabrication and measuring machines [2]. Among others, Bryan and Cater summarized: "Real straightedges are not perfectly straight, so that errors in the shape of the straightedge become mixed with the machine-slideway errors that we are trying to measure" [3]. Therefore, error separation methods are used to separate the slide straightness error and the straightness deviation of a sample. They are based on the utilisation of several sensors, several measurements of a sample in different positions and orientations or a combination of both [4]. In all cases still a stable reference is needed. For example, reversal techniques require either a stable mirror topography or a reproducible slide straightness error. This requirement might be violated with a different load on the sample carriage coming along with different measurement tasks at the NMC, which is used for calibrations of line scales [5], encoder systems [6] and photomasks [7]. For this reason, the "Traceable Multi-Sensor" (TMS) method [8], which is based on stable angle measurements as reference, was implemented for straightness measurements and was validated with measurements of a dedicated encoder system.

2. Implementation of straightness measurements

2.1. Realization at the Nanometer Comparator

The NMC has been equipped with a new sample carriage providing a mirror parallel to its long-range measurement axis [9] (X-axis) and three new heterodyne interferometers. The Y-interferometers were realized using one glass structure, pictured in figure 1. Their design and performance were based on a previously proposed differential plane mirror interferometer [10]. The periodic nonlinearities were minimized by means of spatially separated input beams, the beam paths through glass were fully compensated and a minimal dead path of the beams in air was realized.

The sample under test was an encoder system consisting of a Heidenhain LIP 38 encoder head and a custom-made scale with a 322 mm long grating. The scale was placed in the sample carriage made of Zerodur on a three-point support. All measurement mirrors of the different interferometer systems were attached to the sample carriage, which was fixed to the moving slide. The slide moved the sample relatively to the bridge, where the encoder head and the reference mirrors of all interferometers were attached to. The frictionless movement on air bearings was recorded by the X-, yaw-, pitch- and three new Y-interferometers. A groove in the granite base of the NMC defined the slideway. The signals of all interferometers and the encoder system were acquired highly simultaneously with two synchronized phase meter boards [11]. Additionally, the signals of the angle interferometers were used as feedback for a close loop control of the piezo elements integrated in the moving slide.

2.2. Using Traceable Multi Sensor method for straightness measurements

The measurement data of the three Y-interferometers and the yaw-interferometer were used to determine the topography of the Y-mirror and the slide straightness error. The measurement process was modelled using a small-angle approximation, which resulted in a system of linear

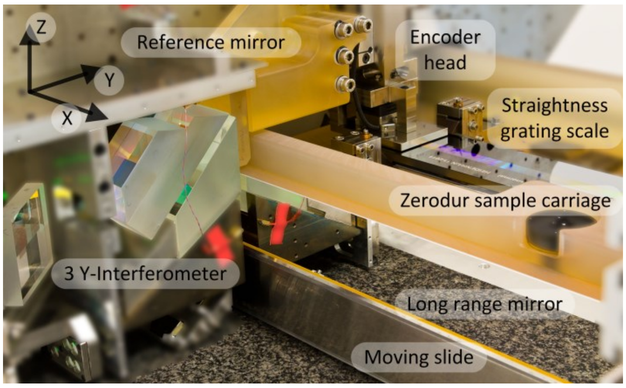

Figure 1. Arrangement of the measurement systems for straightness measurements at the Nanometer Comparator.

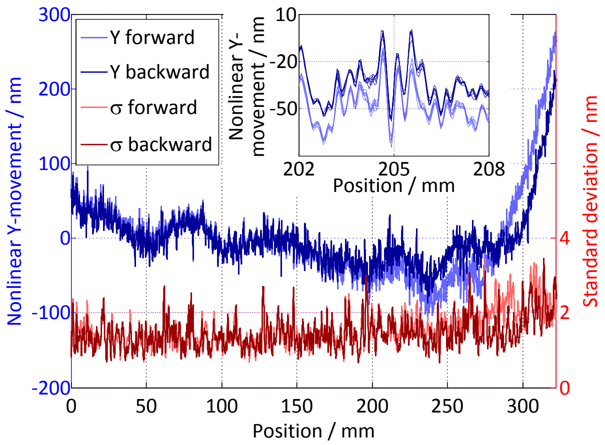

Figure 2. The average slide straightness errors differed between the forward and backward movement of the slide. The inset emphasizes, that the reconstructed guiding errors were dominated by high spatial frequencies and not by noise.

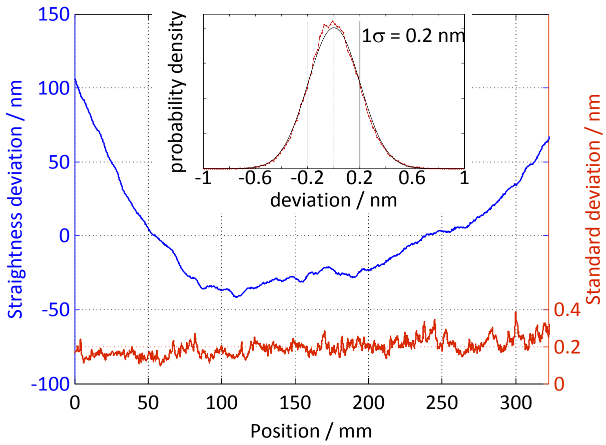

Figure 3. The evaluated straightness deviation of the grating scale was independent of the movement direction. Each measurement varied with a standard deviation of 0.2 nm around the common mean of 14 measurements, as illustrated with the inset.

equations [8]. The mirror topography was interpolated with Lagrange polynomials to allow a non-equidistant interspacing of the sensors and measurement points [12]. Coprime interspaces between the Y-interferometers led to a higher lateral resolution of the reconstruction results [12], which is equivalent to rotational shears at a three-flat test [13].The reconstructed slide straightness error was subtracted from the measurement values of the encoder system to obtain the straightness deviation of the scale.

3. Measurement results

During one measurement series the straightness deviation was evaluated 14 times with the TMS method, each 7 times for the slide moving in positive and negative X-direction. During the straightness measurements the slide was moved with a speed of 2 mm/s. The averages over each 2000 measurement values were calculated resulting in an interspace of 82 µm between the measurement points in X-direction and yielding to equation systems with a manageable size. The equation systems were solved by means of a weighted least-square method. The covariance matrix of the measurement values was used as weight and an interspacing between the topography reconstruction points of 1 mm was chosen, which provided an adequate lateral resolution compared to a Y-interferometer's beam diameter of 4.1 mm.

3.1. Slide straightness error and straightness deviation

The reconstructed slide straightness errors are illustrated in figure 2. They were different depending on the moving direction of the slide. But within one direction they were repeatable with a standard deviation below 2 nm. Each of 14 slide straightness errors was subtracted from the measurement values of the encoder system resulting in the straightness deviation of the scale. The evaluated straightness deviations were independent of the moving direction and the average is shown in figure 3. Each measurement varied with a standard deviation of 0.2 nm normally distributed around the common mean, resulting in a standard deviation of the mean of 53 pm.

3.2. Uncertainty and outlook

13 measurement series were performed with different orientations and positions of the scale inside the Zerodur sample carriage. The repeatability was for each series below 0.1 nm. But the reproducibility of the straightness measurements was in the nanometre range, because of a length depending error of the yaw-interferometer. This error was determined within a comparison using a calibrated autocollimator [14, 15] and dominated the uncertainty of the straightness measurements using the TMS method. The standard uncertainty of the average of the 13 measurement series was evaluated to be 1.23 nm and confirmed in a comparison with another error separation method based on a reversal technique.

With the continuous determination of the mirror topography and the slide straightness errors for different loads on the moving slide they can be compensated every time anew and their potential influence on registration measurements can be reduced. Straightness calibrations with sub-nanometre uncertainties will be achievable at the NMC with an improved yaw-interferometer.

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