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A new sensor for one-dimensional tactile measurements with the Nanometer Comparator

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Abstract
We report on the development of a tactile sensor on a silicon flexure whose deflection is measured with two fibre interferometers. It will be used to realize one-dimensional tactile measurements, like step gauge calibrations, with the Nanometer Comparator of PTB. For repetitively probing a face of a gauge block, a standard deviation of less than 7 nm was achieved.

Keywords: Tactile sensor, interferometry, calibration, step gauge

1. Introduction

To meet the increasing uncertainty demands for the calibration of tactile coordinate measuring machines the PTB aims to provide calibrated artefacts with an uncertainty in the range of 30 nm. Therefore, the Nanometer Comparator (NMC) will be upgraded with a tactile sensor system to add the capability to measure step gauges. The NMC is the national standard of Germany for the calibration of line scales, photo masks and encoder systems with uncertainties in the single-digit nanometre range. It features a slide with a moving range of up to 600 mm (in X-direction) whose position is controlled using the feedback of three interferometers working in vacuum [1]. At any position of the moving range the slide position varies with a standard deviation of less than 0.3 nm [2] and the linearity of the motion is in the range of ±1 nm [3]. But the moving range of the slide is limited to ±5 µm in Y- and Z-direction. Therefore, the tactile sensor must be moved in Z-direction with an additional stage with a moving range of up to 50 mm. The expected guiding errors of the additional Z-stage would limit the measurement uncertainty in case a conventional commercial tactile sensor is used. Therefore, a new sensors concept was tested.

2. Upgrade of the Nanometer Comparator

Figure 1 is giving a schematic drawing of the NMC structure. The step gauge will be placed inside a sample carriage made of Zerodur [4] on the moving slide. The moving mirrors of all interferometer systems are attached to the sample carriage. Therefore, the mirrors are linked with the measurement object in a stiff way and temperature variations cause only negligible distortions. The probing system will be mounted on the bridge connected with the reference mirrors of the interferometer systems. Since the NMC was not specially designed for step gauge calibrations, space restrictions for potential measurement objects have to be considered. Heights must be smaller than 70 mm, width smaller than 65 mm and length below 550 mm. The tactile sensor must be moved in Z-direction with an extra stage, which shows a nonreproducibility in the vertical motion direction of some nanometre.

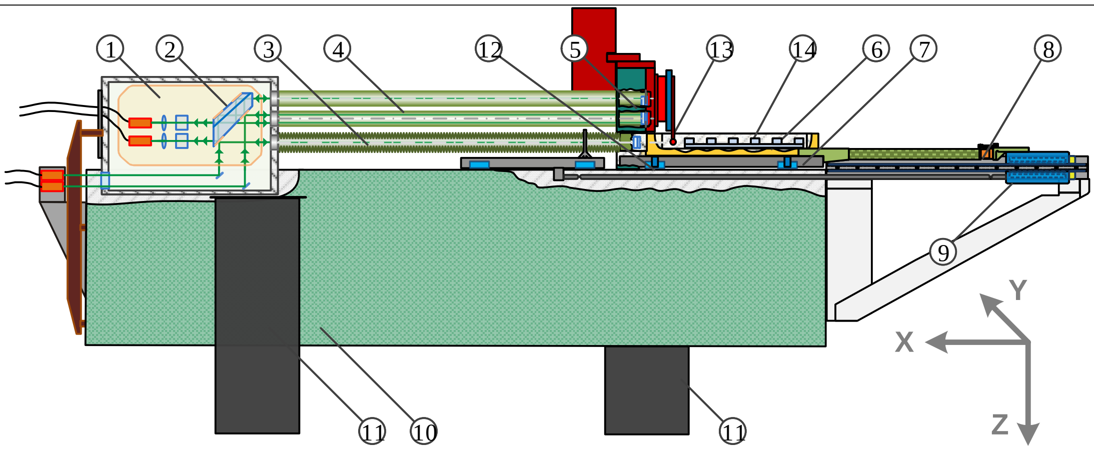

Figure 1: Schematic drawing of the Nanometer Comparator: 1: vacuum chamber for the X-, yaw- and pitch-interferometers, 2: X-interferometer beam splitter [1], 3: vacuum bellow connecting the moving slide and the vacuum chamber guiding the measurement beams, 4: pipes for the reference beams of the interferometers, 5: bridge with all reference mirrors, 6: sample carriage with long-range Y-mirror and moving mirrors of the vacuum interferometers [4], 7: moving slide, 8+9: Lorentz actuator and linear motor for the positioning of the slide, 10: granite base (size: 3,15x0,8x0,7 m³), 11: active vibration isolation, 12: piezo elements connecting the air bearings and the slide 13: tactile sensor with Z-stage connected to the bridge, 14: step gauge mounted on the sample carriage.

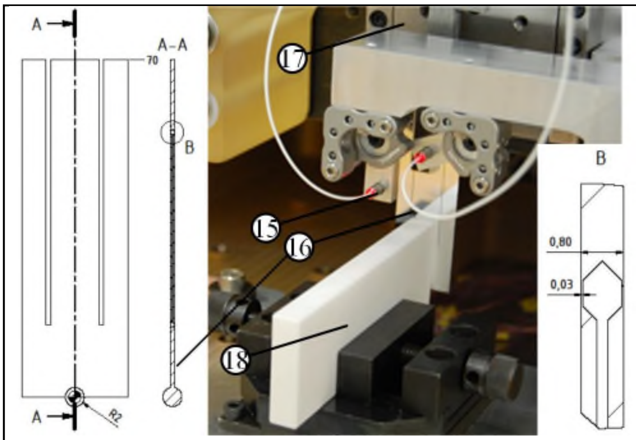

Figure 2: Tactile sensor probing a gauge block (18), mounted on a Z-stage (17), based on a silicon flexure with aluminium coating (16) whose deflection is measured with fibre interferometers (15).

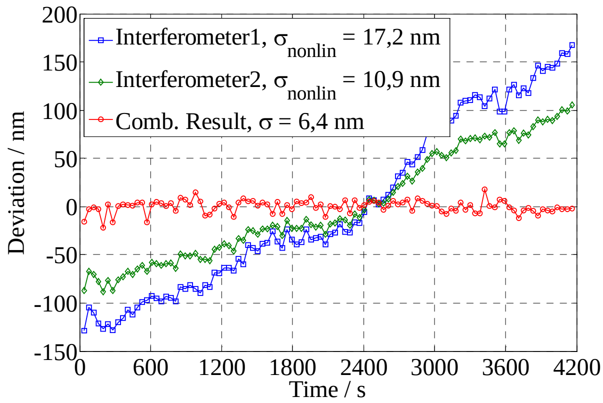

Figure 3: Repeatability of probing a gauge block while the stylus was deflected up to 48 µm, which was measured with two interferometer heads arranged at different Z positions to compensate for the angle variations of the tactile sensor.

To compensate for this nonreproducibility, a mirror was integrated in the tactile sensor, which position is measured by an interferometer fixed directly to the bridge. This allows for measuring the stage position and can additionally be used to detect the probing process. The interferometer is measuring at least 45 mm above the probing point of the sphere, therefore a second interferometer must be integrated to compensate for pitch angle variations of the Z-stage [5].

3. The opto-tactile sensor

The tactile probe consisted of an etched silicon stylus coated with aluminium. The stylus is illustrated in figure 2. In opposite to conventional styli its bending is a desired effect. Therefore, the thickness of the silicon wafer was reduced at certain positions by wet-chemical etching resulting in a double beam configuration with flexure hinges. This configuration enables a nearly parallel movement of the two mirrors arranged on the left and right side of the central flexure. To avoid a reduction of the signal amplitude of the two interferometers measuring the deflection, the angle variations caused by the deflection of the stylus must be minimal. These mirrors had a length of 70 mm to measure the repeatability of the motion errors of the Z-stage without interruption of the interferometer beams.

The errors and the stability of the fibre interferometers influence the measurement results directly. The miniaturised Michelson type measurement heads were fully-fibre coupled separating the stabilized 1532 nm (IR) laser source and the signal processing unit as heat sources from the setup. The laser frequency was modulated to generate quadrature signals. This leads to the drawbacks of periodic nonlinearities and the need of a dead path of at least 13 mm, so that variations of the ambient conditions influence their long-time stability. Therefore, this IR interferometer was analysed in preliminary experiments in comparison with the X-interferometer of the NMC revealing a long-term stability of the system in the range of ±2 nm over 5 hours and periodic nonlinearities with an amplitude of 3.6 nm [6].

The chosen dimensional parameters of the stylus resulted into a potential elastic deflection of several hundred micrometres, but also into a high sensitivity to vibrations. Without contact to the surface the sphere with a diameter of 4 mm glued to the stylus oscillated with an amplitude of up to 1 µm with the eigenfrequency of the stylus of 10 Hz. These oscillations were significantly reduced to an amplitude below 30 nm in case the sphere was in contact with a face of a gauge block. The two interferometer heads measuring the deflection of the stylus were arranged at different Z positions. Their interspace was approximately three times smaller than the distance between the first interferometer head and the sphere, which was located collinear with the measurement beam of the X-interferometer of the NMC.

4. Repetitively probing a gauge block

A gauge block mounted on the moving slide of the NMC was moved with 5 µm/s and repetitively probed 102 times. For each probing point a line was fitted to the interferometer data with a deflection of the stylus between 6 µm and 46 µm. Without subtracting the zero-deflection level for each probing the zero-force point was calculated keeping the reference to the first probing with the stability of the IR interferometers. As shown in figure 3, a use of only one interferometer would result into a long-term drift of the zero-force point. But, calculating the difference of the two interferometric measurements and compensating for angle variations resulted into a reduction of the standard deviation to 6.4 nm. The remaining deviations are likely to be caused by the periodic nonlinearities of the IR interferometer, the influence of refractive index variations and mainly the oscillation of the stylus.

The required size of the stylus in combination with the comparatively soft flexures to realize a parallel movement of the mirrors with the sphere resulted a high sensitivity to vibrations even in the case of contact. Therefore, the oscillations of the stylus limited the repeatability of probing a gauge block. A reduction of these oscillations will be the focus of future developments.

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