Redetermination of the Abbe Errors' Uncertainty Contributions at the Nanometer Comparator

R. Köning, C. Weichert, P.Köchert, J. Guan, J.Flügge

Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany
Email: rainer.koening@ptb.de

Abstract. *The measurements of the angle deviations of the measurement slide and the determination of the measurement line were repeated in the course of the ongoing upgrade of the Nanometer Comparator, the current line scale interferometer of the PTB. The results show that the use of calibrated angle interferometers in angular control loops reduces the angle deviations significantly, but does not eliminate them completely. The Abbe offsets and the position of the measurement line of the interferometer in the vacuum enclosure are determined with the aid of a high resolution incremental encoder. Finally, we demonstrate that by aligning the measurement object to the measurement line and by closing the angular control loops, the Abbe errors can be reduced to negligible levels even for the most demanding dimensional metrology tasks.*

Keywords: Line Scale Interferometer, Vacuum Interferometry, Abbe Error, Measurement Uncertainty

1. Introduction

The Nanometer Comparator [1] provides traceable measurements of line scales, photo-masks, incremental encoders and interferometers in the range up to 540 mm with expanded measurement uncertainties of a few nanometer only. This level of uncertainty is reached by operating the optical interferometers, which are well integrated in the mechanical setup, completely in vacuum. In the ongoing upgrade [2] the Nanometer Comparator is equipped with a Zerodur sample carrier that contains a mirror at one sidewall parallel to the measurement direction, which will be used by an additional interferometer to allow straightness reference measurements [2]. In order to determine the mirror topography the TMS method [3] will be implemented.

Abbe errors are important uncertainty sources in many dimensional metrology tasks [4]. They occur if the measurement lines of the measurement object and the reference displacement interferometer do not agree and an angular motion between the two measurement systems occurs during the measurement, e.g. by guidance deviations of a slide. The value of the Abbe error Δx in the measurement direction x is given in first order by

$$\Delta x = d_y \times \Delta\varphi_z + d_z \times \Delta\varphi_y, \quad (1)$$

where

d_y, d_z	Distance between the measurement lines in y, z-direction, Abbe offsets
$\Delta\varphi_y$, $\Delta\varphi_z$	Change of rotation angle about the y- and z-axis, Pitch and Yaw

In order to minimize this uncertainty contribution at the Nanometer Comparator, vacuum angle interferometers and piezoelectric actuators are used together in control loops. Furthermore, for a reliable determination of the remaining Abbe errors, the angle deviations in closed loop mode and the Abbe offsets still need to be determined. Once the Abbe offsets are determined, the location of measurement line of the displacement interferometer is known as well. In order to reduce the Abbe errors even further, in all subsequent measurements, the measurement object will be aligned such that the Abbe offsets nominally vanish. These experimental investigations have already been performed some years ago [5] but had to be repeated recently, because the new sample carrier adds a substantial amount of weight to the measurement slide and its installation required a realignment of all interferometers.

2. Measurements and Results

Measurement Setup

For the calibration of the angular vacuum interferometers and the determination of the position-dependent angle deviation of the angular control loops a high resolution autocollimator (Möller Wedel HR) was employed. It has been calibrated in the central region about zero with an uncertainty of 44 nrad internally at the PTB [6]. The measurement setup is shown in the left schematic of Fig. 1. Due to its large weight and size, the autocollimator was

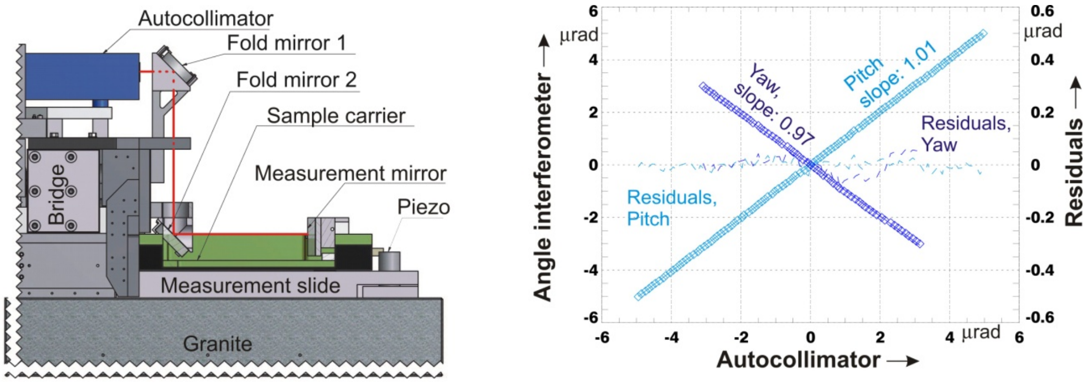

Fig.1. Setup of Autocollimator measurements (left) and the calibration results of the angle interferometers

located on top of the bridge. Its beam was directed by two fold mirrors parallel to the motion axis of the measurement slide and orthogonal to a measurement mirror fixed at the sample carrier. To assure this alignment, a laser beam of 3 mm diameter was aligned parallel to that motion axis by means of a quadrant detector. Then the measurement mirror was aligned using the inference pattern of the incoming and reflected beam. The measurement mirror was aligned until less than one interference fringe remained visible, which is equivalent to a remaining misalignment smaller than 200 µrad.

Calibration of the vacuum angle interferometers

First the angle interferometers need to be calibrated because the distance of their beams, which is required to determine the angle change to be measured cannot be measured with sufficient accuracy directly. Furthermore due to deviations of the beam profile from a Gaussian shape additional deviations are likely to occur. The diagram on the right side of

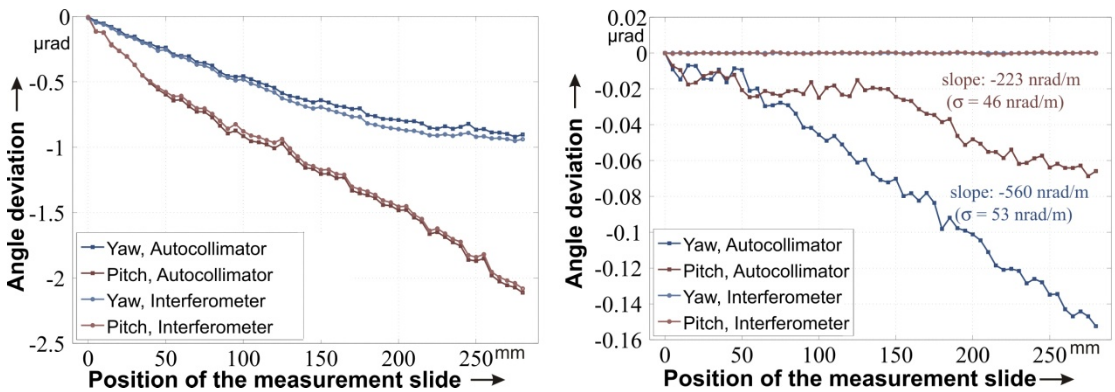

Fig. 2. Dependence of angle deviation on the position of the measurement slide without (left diagram) and with (right diagram) angular control loop.

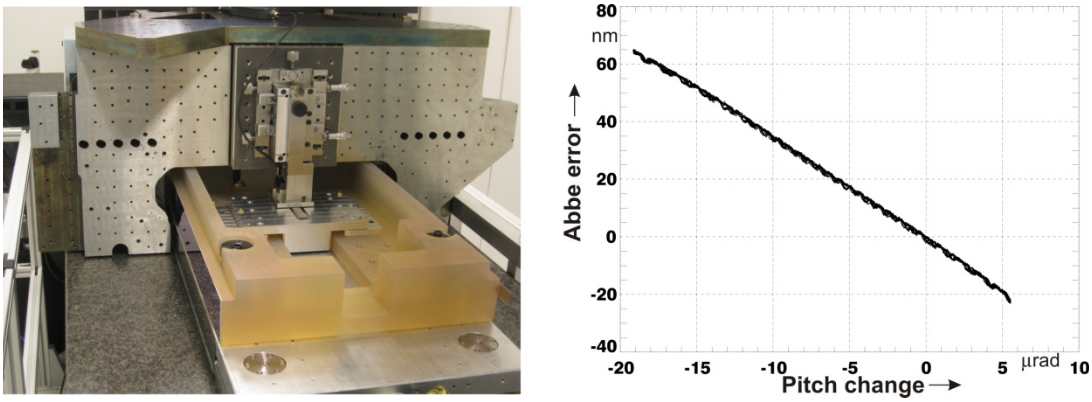

Fig. 3. Image of the measurement setup for incremental encoders (left) and Abbe error introduced by a pitch change with an intentionally enlarged Abbe offset (right)

Fig. 1 shows the results of a calibration of both angle axes at a fixed position within the measurement range. For this purpose the angular orientation of the measurement slide was changed by the piezoelectric elements and the resulting angular motion was measured by the autocollimator and the interferometer. The calibration constant varied a few percent if the calibration was repeated at different positions of the slide. The obtained variation of the calibration constant was within the scattering range observed if the experiment is repeated at the same location.

Determination of the Position-dependent Angle Deviation in Closed Loop Mode

During the length measurements the angular control loops are closed to maintain the angular orientation of the measurement slide. In this case the angle deviations measured by the autocollimator, which occur while moving the slide over the measurement range, has to be taken into account for the determination of uncertainty contribution of the Abbe error. Fig.2 shows the dependence of angle deviations in open and closed mode on the position of the measurement slide. The measurement range was limited by the position of the measurement mirror in the sample carrier to 280 mm. But this still comprises the measurement range used for the most accurate measurements. However, the right diagram reveals that the use of the control loops reduces the angle deviations by more than a factor of 10, but does not eliminate them completely. This leads to an uncertainty contribution of 73 nrad for the yaw interferometer and 51 nrad for the pitch interferometer.

Determination and Reduction of the Abbe Offsets, Measurements using an Incremental Encoder

Abbe errors can be observed instantly if another displacement sensor is compared to the displacement interferometer of the Nanometer Comparator. If an angle change is introduced by the piezoelectric elements intentionally and reported in addition to the related Abbe error then the Abbe offset can be determined as well. Here, a high resolution incremental encoder (Heidenhain LIP 382), which already has proven to be a valuable tool in the characterization of the displacement interferometer [7], was used again. An image of the setup is shown in the left part of Fig. 3. An example of the Abbe error caused by a pitch change is illustrated in the right diagram of Fig.3. In this case the incremental system was mounted intentionally about 3 mm above the measurement line of the interferometer. Fig. 4 shows the result of a change of Yaw and Pitch for an optimized alignment of the measurement lines of the incremental encoder and displacement interferometer of the Nanometer Comparator. The remaining Abbe offsets d_z and d_y are estimated to -0.03 mm and 0.16 mm, respectively.

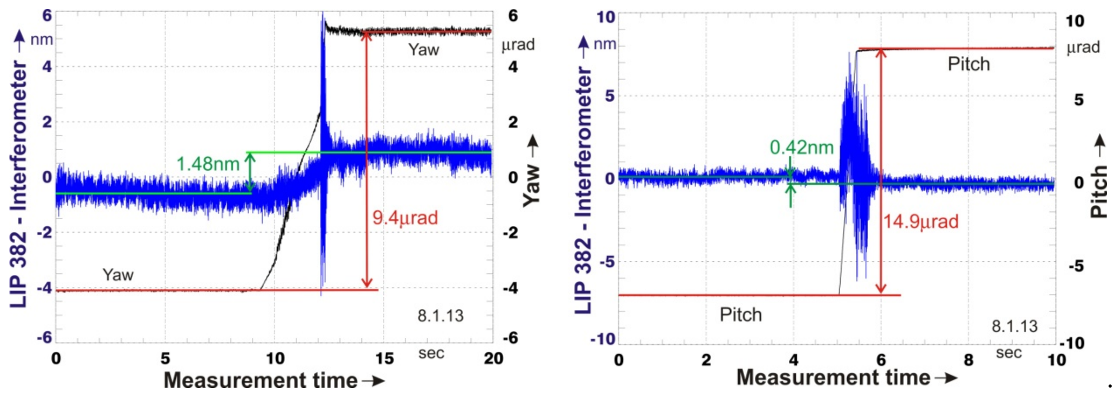

Fig. 4. Remaining Abbe errors after an optimized alignment

3. Conclusions

The results of Fig. 2 show that position-dependent angle deviations occur although calibrated angular interferometers are used in control loops to correct them. A further discussion of the origin of these deviations and the limitations of the whole approach is beyond the scope of this paper. However, these deviations lead to residual Abbe errors, which need to be included in the measurement uncertainty estimation. In order to reduce this uncertainty contribution even further, we demonstrated that the piezoelectric actuators and the angle interferometers can be used to optimize the alignment of the measurement object, so that the Abbe offsets almost vanish. In this case the remaining uncertainty contribution, even if calculated under worst case assumptions (all length dependent angle deviations are caused by the angle interferometer, both contributions added and uncertainty of the calibration included as well), remains negligible.

This approach can be applied as well to other dimensional metrology systems equipped with angular control loops. It allows not only the reduction of the Abbe errors but also to determine the Abbe offsets and the remaining Abbe uncertainty contributions in a reliable way.

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