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Interferometric calibration of a high-accuracy piezo actuator at FSB-LPMD

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Abstract

Piezo actuators are commonly used in dimensional metrology, either for high accuracy positioning tasks or for direct measurement of displacement. Providing traceability for these devices can be challenging because of high resolutions that can be achieved over short displacements. Additionally, closed-loop actuators are usually very constrained with regard to the loads they can carry. For example, this research was carried out on a piezo actuator with 100 µm displacement, minimum step size of 0.3 nm, and maximum normal force of 10 N. Sensitivity of typically used displacement interferometers can be insufficient for such parameters, and the weight of target optics can be outside of acceptable range for closed-loop positioning. For these reasons, we decided to investigate the applicability of a gauge block interferometer for this task. The described method was used for a highly-detailed calibration over the entire range of motion of a vertical piezo actuator, with step size less than used half-wavelength, using custom software to drive the actuator and analyse interferograms for each step. A detailed description of the method is provided together with the measurement results for an example piezo actuator.

Keywords: Piezo actuator, interferometer, traceability

1. Introduction

Piezo actuators are often used in dimensional metrology, either as open-loop nano-stepping stages, or as closed-loop nano-positioning stages. Their use in metrology spans direct calibration of various stylus instruments [1], phase-stepping generation in phase stepping interferometry [2], to scanning stages for atomic force microscopy [3]. Given the high resolutions and minimum step sizes these devices can achieve, optical interferometry is one of the few suitable methods that can be used to calibrate them. Review of available literature shows that most calibration methods rely on variations of displacement interferometry [4], where a piezo actuator is carrying the measurement mirror of a displacement interferometer. Even though this approach can provide sufficient measurement accuracy, down to picometre range, commercially available displacement interferometers typically only provide nanometre resolutions. Additionally, commercially available displacement interferometers usually employ retroreflecting optics to increase useful measurement range, which can be too heavy to use on a closed-loop vertical piezo stage.

Static interferometry, typically used for gauge block calibration, can provide very high resolution but the measurement range is limited to only half of used wavelength. This method can be used to calibrate a vertical piezo actuator at several nominal displacement positions, but in that case an assumption needs to be made that there are no errors larger than half of wavelength (usually 250 nm - 350 nm) between the measured positions, due to periodic nature of static interferograms. Based on specifications of typically used high-accuracy piezo actuators, this is usually a valid assumption, but it would nevertheless be more desirable to test the entire range of motion to reliably determine positioning errors.

2. Methodology

In order to provide a pseudo-continuous measurement of entire range of motion of vertical piezo actuator using static interferometry, a gauge block interferometer was used to acquire interferograms at positions that correspond to slightly less than one third of its half-wavelength. This approach should provide sufficient measurement data to connect each interferogram over the entire measurement range, resulting with continuous measurement data.

Measurement setup consists of a vertical piezo actuator (PI P-621.ZCD) which is placed in a gauge block interferometer (Zeiss Kosters type, retrofitted at FSB-LPMD). A wedged gauge block platen, placed on the piezo actuator, is used as the measurement mirror. Gauge block interferometer was adjusted to show several vertical interference fringes over its field of view at the start position. A custom software package is used to control the piezo actuator and automatically acquire interferograms after 200 ms settling time. Piezo actuator was positioned with 100 nm step size over 100 µm range, resulting with acquisition of 1000 interferograms which were processed with a custom fringe analysis algorithm. Fringe analysis was based on locally adaptive threshold edge detection to determine fringe centres, after which a least squares line was fitted to each fringe centre. Fringe spacing was calculated as the distance between adjacent fringe centre lines, and provides the metric for measurement of piezo actuator motion – fringe spacing being equal to half of used wavelength (632.8 nm). Measurement of each displacement is performed recursively, using data from previous step to calculate the difference from current step (Figure 1).

3. Measurement results

After acquisition and processing of the entire range of measurement data, as described in previous chapter, results of

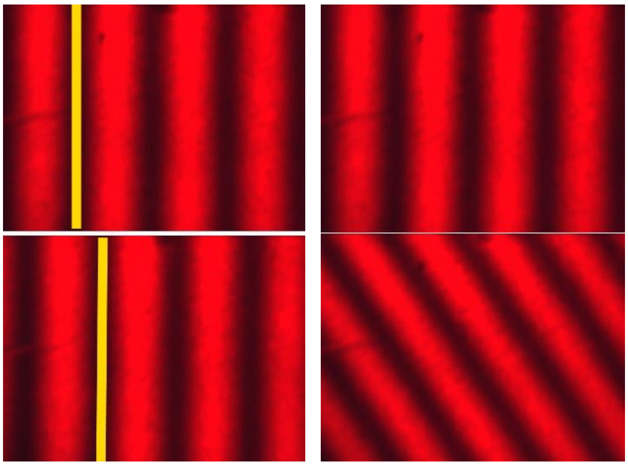

Figure 1. Interferograms of two consecutive positions of piezo actuator spaced apart 100 nm (left top and bottom); fringe angle variation over total displacement (right top and bottom) .

positioning error analysis showed that individual step errors are all within ± 10 nm, while cumulative positioning error is below 110 nm (Figure 2). These results indicate that calibration can be performed by setting displacements equal to nominal number of half-wavelengths and then measuring the deviation from those nominal values, since it is proven that there are no errors larger than half-wavelength over the entire displacement range. In that case, accumulation of individual step errors, which is present in the data shown in Figure 2 (“Cumulative positioning error”), will be eliminated.

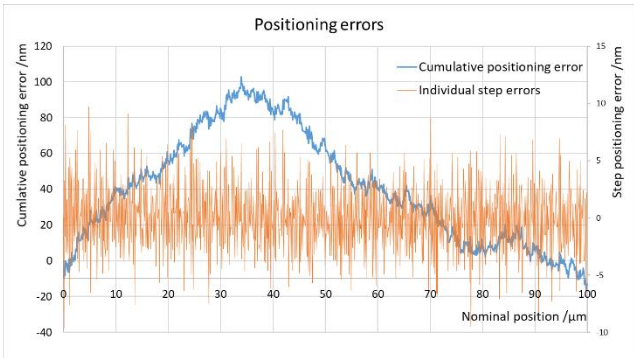

Figure 2. Positioning error measurement results.

Additionally, yaw and pitch angle errors show a significant contribution to the angle variation of interference fringes over the entire range of motion (Figure 1, right). Since these errors would negatively impact measurement accuracy if they were ignored, it was decided to try to simultaneously measure both positioning and pitch/yaw errors of the piezo actuator.

Pitch and yaw angle errors were estimated from the change in fringe angle between subsequent positions, according to Figure 3 and the following simple equations [5]:

$$Yaw\ error = \frac{\lambda}{2}\left(\frac{1}{\Delta Y} - \frac{1}{\Delta Y'}\right) \qquad (1)$$

$$Pitch\ error = \frac{\lambda}{2}\left(\frac{1}{\Delta X} - \frac{1}{\Delta X'}\right) \qquad (2)$$

For simplicity, this procedure is currently only implemented in 10 µm steps and its results are shown in Figure 4. Results show that yaw angle errors range from -1 arc second to 3.5 arc seconds, while pitch angle errors are negligible, within ± 0.5 arc seconds.

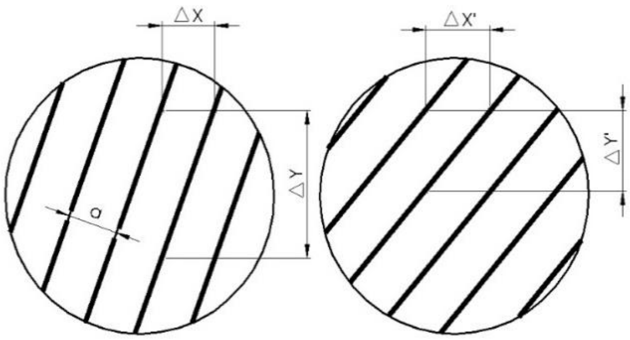

Figure 3. Schematic of yaw and pitch angle error measurement.

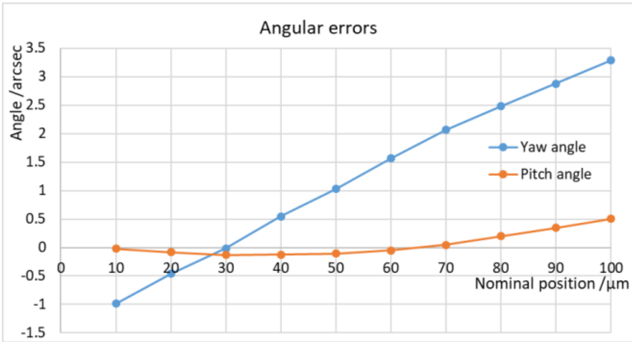

Figure 4. Angular error measurement results.

4. Conclusion

We presented the foundations of a simple procedure for simultaneous measurement of positioning and pitch/yaw errors of a vertical piezo actuator stage, using a gauge block interferometer and simple analysis methods. Due to periodic nature of interferograms, a possible error could arise if the displacement of a piezo actuator contains errors larger than half-wavelength used for measurement. It was shown that this error can successfully be eliminated by making a pseudo-continuous measurement, with displacement steps smaller than the half-wavelength. In order to fully calibrate the piezo actuator stage, it is necessary to eliminate accumulation of individual step errors over the entire displacement range, using integer half-wavelength displacements as nominal displacement steps and measuring only the deviation from those nominal values. Future development will also focus on additional measurements with a displacement interferometer to provide an independent confirmation of results, as well as on improvements to angle measuring algorithm to also provide continuous measurement of angle.

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