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Traceable characterisation of high-precision moving stages with displacement resolutions down to 10 pm

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Abstract
A reliable calibration setup for the investigation of the quasi-static performance of moving stages is reported. As one of the key components in the calibration system, an NPL differential plane mirror interferometer is used to measure the displacement of different stages. To minimize potential systematic errors, the mechanical system of the calibration setup has been well designed so that the interferometric measurement system should have zero-path difference. First experimental results have proven that the calibration setup under nearly open-air conditions can achieve a resolution of 14 pm and a noise floor better than 10 pm/ $\sqrt{\text{Hz}}$ over 2 Hz bandwidth. Commercially available stages have been characterised with this calibration setup.

Keywords: Nanometrology, homodyne laser interferometry, high-precision moving stage, displacement measurement, capacitive sensor calibration

1. Introduction

Rapid advances in manufacturing and sensing techniques enable that more and more ultra-precision moving stages with a nominal displacement resolution down to sub-100 pm have been developed, and have become commercially available [1-2]. For the purpose of quantitative quality control of these stages, traceable calibration approaches with a resolution down to 10 pm are therefore required.

2. Principle

An interferometric calibration setup (shown in Fig. 1) for investigation of the quasi-static performance of moving stages has been realized. As one of the key components of the calibration system, a differential plane mirror interferometer developed at NPL(National Physical Laboratory, UK) [3] is used to measure the displacement of different stages.

The laser light (λ = 632.8 nm) coming from a frequency-stabilized He-Ne laser (SIOS) is firstly coupled into a polarisation-maintaining single mode fiber and then delivered to the interferometric calibration setup, enabling high flexibility of the calibration system. A fiber-coupled collimator (CL_2) is used to collimate the output light from the fiber, yielding a well-collimated laser beam with a beam diameter of about 1 mm. After passing through the interferometer block , two pairs of parallel beams are generated, among them the inner beam pair is used to detect the displacement of the piezostage, and the outer beam pair is reflected back by an u-shaped reference mirror with a flatness better than λ/10.

The reference mirror is directly mounted onto the interferometer block with fine adjustment capability. The measurement mirror is fixed to the moving stage under calibration.

To reduce further potential systematic errors, the mechanical system of the calibration setup has been well designed so that the interferometric measurement system should have zero-path difference.

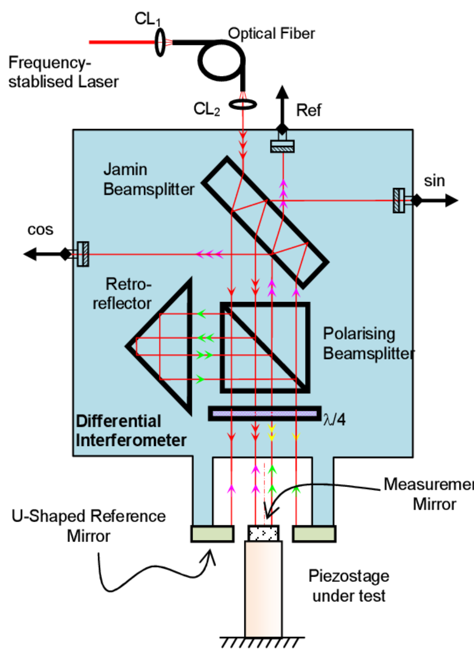

Figure 1. Principle of the calibration setup for experimental investigation of the quasi-static performance of moving stages. (Note: The configuration shown here is designed for calibration of the vertical axis of a piezo-positioning stage).

3. Experimental investigation

The phase-quadrature interferometer signals (i.e. sin and cos in Fig. 1) are acquired by a FPGA DAQ board (National Instruments, 16 Bits) with the DAQ sampling rate of 70 kHz, and decoded by a LabView-based program with a typical data sampling rate of about 1 kHz.

Electrical drive and displacement sensing of the precision positioning stages are delivered by the manufacturers, accordingly.

3.1. Noise floor of the interferometric calibration setup

After careful determination of the Heydemann [4] parameters and nonlinear correction of the NPL differential plane mirror interferometer, the noise spectrum of the calibration setup has been experimentally investigated, and is illustrated in Fig. 2, where a low-pass filter with $f_{\text{cut-off}}$ = 50 Hz has been applied.

Although the calibration setup has a relatively poor vibration isolation (e.g. resonance frequency at about 7 Hz), it can be seen from Fig. 2 that a noise floor better than 14 pm/ $\sqrt{\text{Hz}}$ can be achieved at frequencies higher than 1 Hz.

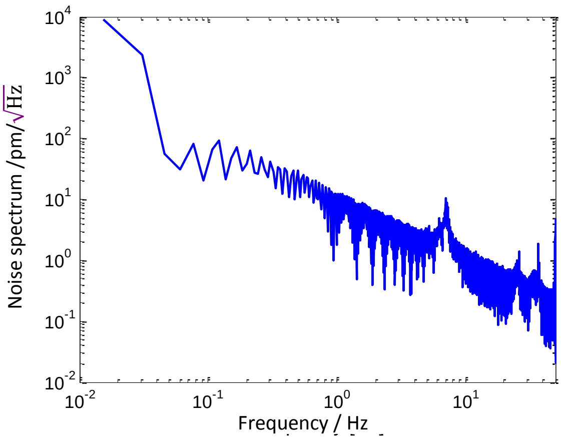

Figure 2. Noise spectrum of the calibration setup at room temperature.

3.2. Determination of the sensitivity of fine-positioning piezo-stages

The calibration setup has firstly been utilized to investigate the sensitivity of a piezostage (P-363, Physik Instrumente (PI)) with capacitive sensor and analogue interface [5]. To drive the y-axis of the piezostage in open-loop mode, a precision voltage source (Burster, DIGISTANT 4462) with basic accuracy 0.005% [6] was used. One of the typical measurement results are depicted in Fig. 3, where the nominal displacement of the piezostage driven by the DC voltage is calculated as $(V_{drv} - V_0)$ * 500 pm/mV. Although the capacitive readout of this piezostage couldn't resolve the real displacement of the stage due to the operation below the specified closed-loop resolution, the interferometric system indicates that, under the condition of open-loop movement, the piezostage is able to realize step-like displacement of 50 pm.

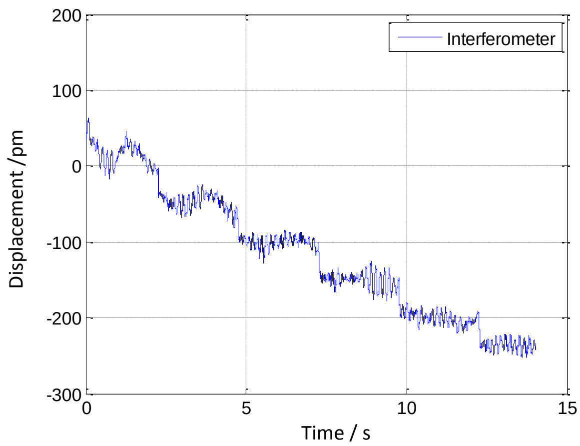

Figure 3. Step-like displacement of the y-axis of the piezostage P-363.3CD in open-loop mode measured by the interferometer with a low-pass filter $f_{\text{cut-off}}$ = 50 Hz.

Figure 4 shows the step-like response of a Nano-HS3M piezostage [7] in closed-loop. Under the conditions of 1 kHz data acquisition and 50 Hz low-pass filtering, the 50 pm step-like displacement of the piezostage can be well measured by the interferometric calibration system with a sensitivity of 25 pm (1σ).

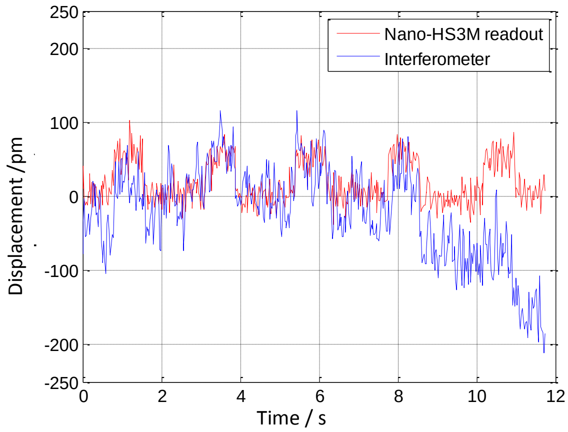

Figure 4. Closed-loop displacement (50 pm steps) of a piezo scanner measured by the integrated PicoQ® sensor and the interferometer, respectively.

3.3. Determination of the linearity of fine-positioning stages

The flexible construction of the calibration setup allows it to calibrate positioning stages with different movement mechanism. Fig. 5 shows the actual displacement of a linear stage driven by piezomotors. Although the scale error of this stage amounts to less than 0.9% over a relative large displacement, its linearity is actually unsatisfactory.

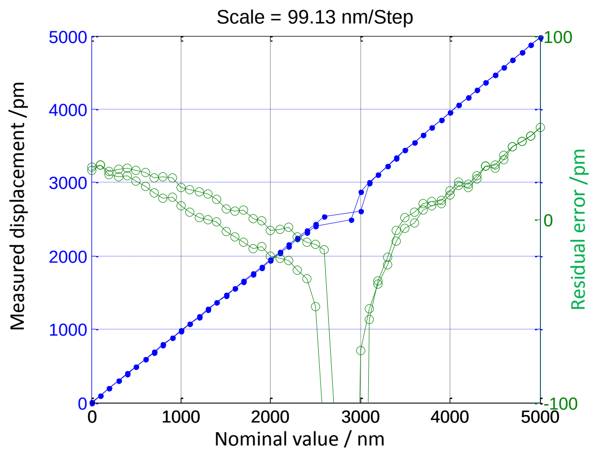

Figure 5. Calibration of the displacement of a piezomotor driven linear stage.

5. Conclusion and acknowledgements

For the purpose of quantitative investigation of the quasi-static performance of moving stages with different movement mechanism und sensing technique, a reliable displacement calibration setup with a resolution down to 10 pm has been realized and reported.

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