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A 100 µm range linear actuator with picometer resolution, subnanometer accuracy and submicroradian tip-tilt error for the characterization of measuring instruments at the nanoscale.

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Abstract
We will present the realization and the characterization of a Picometer Reference Actuator (PRA), a metrological instrument based on a precision linear actuator capable of 100 µm range with subnanometer accuracy, picometer resolution, and submicroradian tip-tilt pointing control. The PRA relies on an integrated multiple reflection homodyne interferometer as a high resolution and accurate internal reference, on a multiple reflection based angle sensor, for the active control of the movement straightness, and on a versatile mirrors configuration to transfer the metrological traceability to an external device. The PRA can be used for critical experiments at the nanoscale as an ultra-precise actuator itself, or as a reference actuator to calibrate displacement sensors. In particular, it has been specially designed to characterize the nonlinearities of high-resolution interferometers at the picometer scale. As an application example, we report the characterization of a heterodyne interferometer in turn dedicated to the calibration of piezo-capacitive actuators.

Keywords: nanometrology, picometer scale, metrological actuator, metrological angle sensor devices, high-resolution interferometry, homodyne interferometer, optical path multiplier.

1. Introduction

The present work has been carried out within the European project NanoTrace [1], a project aimed to achieve a 10 pm accuracy for displacement metrology by developing the next generation optical interferometers to meet the developments in standards and regulatory frameworks, the new technologies in scanning probe microscopy and the advances in co-ordinate metrology [2].

It is well known that the main limit of optical interferometers is the periodical nonlinearity that arises from the non-ideal optical components. The typical accuracy of a commercial interferometer is limited to hundreds of picometers. To characterize a high performance optical interferometer an actuator having negligible (or known) overall errors must be used to displace the target mirror observed by the interferometer itself. Within the project NanoTrace, the ultimate performance of all the involved interferometers have been defined by direct comparison with the x-ray interferometer (XRI) operating at NPL which has an intrinsic picometer level accuracy [3]. The complexity of the XRI limits it usability opportunity, being practically unmovable from the laboratory. The need of a transportable actuator capable of picometer resolution and nonlinearity for the characterization of high performance interferometers has been the driver of the present work. Besides the picometer level accuracy, the candidate actuator must have also extreme pointing capability (very low angle errors) to prevent alignment errors in the interferometer measurement. Precision actuators having sub nanometer resolution are commercially available; nevertheless, neither the accuracy nor the tip tilt errors are simultaneously good enough for the purpose of the project. Therefore, we have built a novel device based on a precision interferometer for the displacement control and on a laser tip-tilt measurement for the straightness control.

2. The actuator

The main purposes of the actuator is to characterize laser interferometers namely in resolution and cyclic nonlinearities. For this reason the interface towards the user have been realized by a fixed mirrors structure symmetrically displaced around a moving mirror assembly so that absolute or differential interferometers can be coupled indifferently. Figure 1 sketches the device with its main components. The base (200 x 200 x 30 mm block) and the main mirrors are made of low CTE ceramic glass assuring a long term stability of all the sensible parts also in poorly thermalized environments.

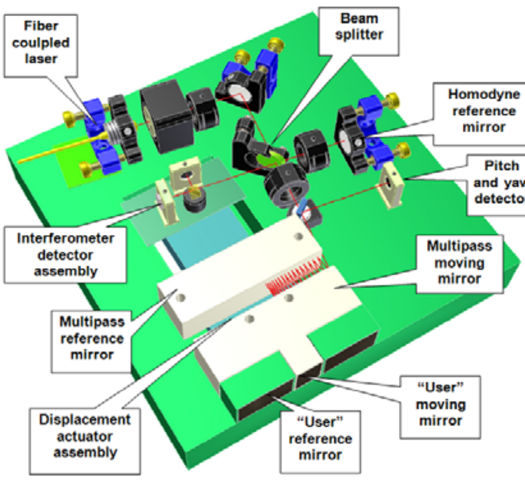

Figure 1. Schematic of the PRA structure

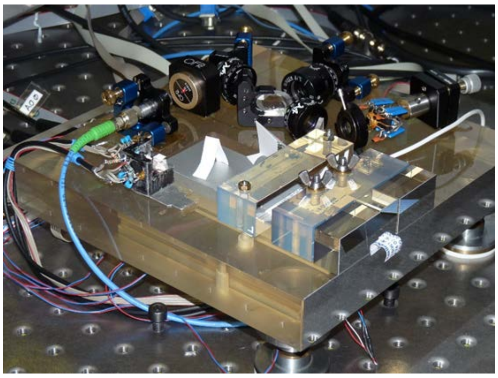

Figure 2. The assembled transfer standard: in the foreground right, the user's mirrors are visible; in the background left are visible the components of the reference interferometer glued to the ceramic glass base.

The base integrates the internal reference multi reflection interferometer which measures the relative displacement between the fixed reference mirror and the moving mirror, displaced by the actuator. The principle and construction details of the multi reflection interferometer can be found in [4]. The other optical elements are mounted on compact commercial precision mounts fixed to the main structure by means of epoxy glue. The laser light feeding the reference interferometer is brought to the bench by means of an optical single mode polarization maintaining fibre. The piezo actuator (NANO OP-100 by MCL) has a 100 µm stroke. Because of the high sensitivity of interferometers to the tilts of the moving mirrors, a particular effort have been done in developing and integrating in the base structure a simple and effective system to compensate the angular displacement error of the long range translation stage. A four-quadrant photodetector sensing the interferometer beam and exploiting the high sensitivity of the multiple reflection principle described in [5] measures the tilt angles. A piezo based pentapode actuator placed under the translation stage corrects for the straightness within fractions of a microradiant.

3. Resolution test results

The resolution of the actuator has been verified by measuring the spectral noise density of the interferometer output. In figure 3 the spectra recorded in different conditions are shown. The blue curves represent the interferometer noise with the angle control on and the pentapode on. As for the multi reflection interferometer described above noise and vibrations are visible in the 300 Hz-3 kHz range, a noise that is well below

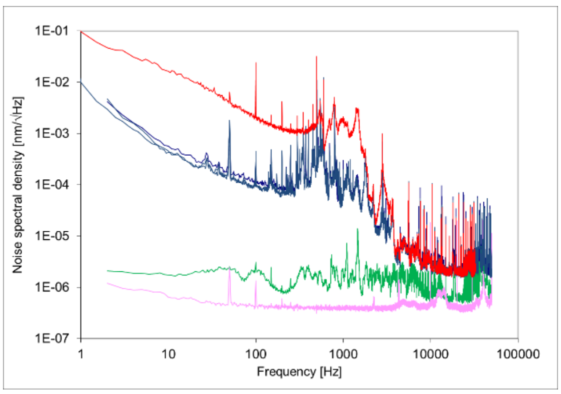

Figure 3. Noise spectral density of the interferometer. See text for detail.

the 1 pm/√Hz level. The noise decreases with below the 1 pm/√Hz level. The noise decreases with frequency down to a few fm/√Hz plateau dominated by electronic noise. The green curve is the detector noise with the laser off and the pink curve is the noise of the electronic board alone. Finally the red curve is the noise of the actuator when the NANO OP-100 is switched on (the noise due to the active control, although very low, is evident).

4. Characterization of an interferometer

In figure 4 is shown the non-linearity characterization of an interferometer used to calibrate piezo-capacitive actuators. Black and white curves in the figure are the readings of the two interferometers after removing the linear component. The two curves, almost identical, show the typical non-linear behaviour of the piezo actuator (about 170 nm over 5 µm). The grey curve is the difference between the two readings represented in the amplified scale on the right. An evident oscillation with 158 nm periodicity is the typical cyclic non linearity expected from a double pass interferometer (633 nm/4) with a value of ± 300 pm p.p..

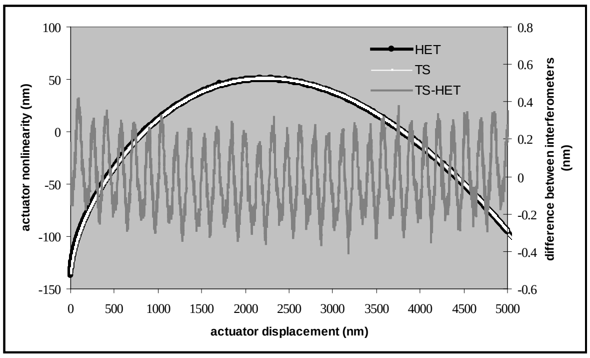

Figure 4. Result of the calibration of a precision interferometer. The actuator is displaced in open loop while the reference interferometer (white curve, left scale) and the interferometer under test (black curve) are recorded. The non linearity of the latter is given by the difference of the two readings (gray curve, right scale).

5. Conclusions

A Picometer Reference Actuator (PRA) controlled by a multiple reflection interferometer and tilt sensor has been realized and characterized. The PRA is made of a low CTE ceramic glass structure where a mirror is accurately displaced with respect to a pair of fixed reference mirrors.

The PRA is compact and easily transportable and can be used to calibrate high-resolution interferometers. Thanks to its long range and very low nonlinearities, its use for the calibration of high performance displacement sensors for nanometrology, such as capacitive sensors and mechanical probes, is foreseen.

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