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Possibilities of calibrating the piezo actuator using the laser interferometer in Croatian National Laboratory for Length

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***Abstract* – Only a few of the most advanced national metrology institutes have a Calibration and Measurement Capabilities calibration service in the BIPM Key Comparison Database to calibrate piezoelectric actuators. Given the importance of precise displacement measurements in various high-precision applications, research on the feasibility of calibrating a piezoelectric actuator using a laser interferometer was conducted at the Croatian National Laboratory for Length. In this research a displacement actuator P – 621.ZCD, manufactured by Physik Instrumente has been calibrated using Renishaw ML10 laser interferometer equipped with an EC10 environmental compensation unit. The calibration was performed within a calibration range of up to 1 µm. The paper provides a detailed description of the measurement procedure, the obtained results, and the evaluation of measurement uncertainty.**

I. INTRODUCTION

Due to the importance of precise displacement measurements in various high-precision applications - such as nanometrology, process control in nanofabrication, semiconductor manufacturing, precision optics alignment, and biomedical device positioning - there is a clear need for traceable displacement actuators.

Only a few national metrology institutes worldwide have developed setups for the calibration of displacement actuators, and even fewer have an officially listed calibration service for displacement actuators in the BIPM KCDB database. Each institute has its own setup, often developed in-house, leading to significant variations in measurement systems used for the calibration of displacement actuators. For example, INRIM as one of these rare institutes, has developed a measurement system based on a heterodyne interferometer. [1]

In 2006, EURAMET launched the Cooperation in Research Project 866, "Interferometric Calibration of Microdisplacement Actuators." This Project brought together eleven laboratories from EURAMET and one laboratory from AFRIMETS. In this Research Project a commercial piezo-capacitive actuator with a range of 10 µm has been calibrated. Due to the metrological challenges involved, the project spanned over a decade and was completed in 2018.

Participants in the project used both homodyne and heterodyne interferometers for displacement measurements. The experimental setups varied significantly between laboratories in several aspects, including the design of optical and mechanical configurations, as well as the orientation of the actuator - tested in horizontal, vertical upward, and vertical downward positions. To compensate for optical non-linearity, participants used different approaches, mostly relying on their correction methods. (As for environmental conditions, participants monitored air parameters using traceable instruments to achieve reliable air refractivity correction.)

Some deviations in full-range displacements was observed over a certain period, affecting measurements performed by three laboratories and one set conducted by the pilot. However, the deviation was not present in repeated calibrations by the pilot a year later. This deviation has influenced the results of these laboratories, likely with a contribution to the uncertainty of the artefact. Hysteresis, drift, and cable bending were also considered as possible sources of error.

For displacements of up to ±5 µm, the results showed some inconsistencies, including possible outliers and a noticeable spread among the measurements. This variation appears to be influenced by undesired actuator rotations (yaw and pitch) when driven through the full displacement range.

In contrast, for short-range displacements within ±100 nm, the results from all laboratories show good mutual agreement, with deviations remaining within the expected measurement uncertainty. [2]

II. MEASUREMENT SETUP

The calibration setup for the piezo actuator, based on laser interferometry, was implemented within the controlled environment of the Croatian National Length

Laboratory. The laboratory foundations are vibration-isolated from the surrounding environment. The measurement setup was mounted on an active anti-vibration optical table. Ambient temperature was maintained at 20 °C ± 0.3 °C. A Renishaw ML10 He-Ne laser interferometer, paired with an EC10 environmental compensation unit and standard optical components, was used for the measurements (Fig. 1).

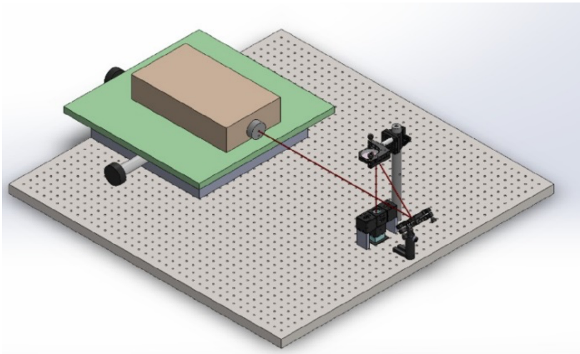

Fig. 1. Measurement setup.

The P–621.ZCD piezo actuator was calibrated with a retroreflector from the interferometric system mounted directly onto it, without mechanical clamping, to avoid introducing additional stress or deformation. To further reduce vibrations potentially arising from system resonances, the piezo–retroreflector assembly was positioned on a damping plate. For improved beam alignment and stability, dielectric mirrors were used (Fig. 2).

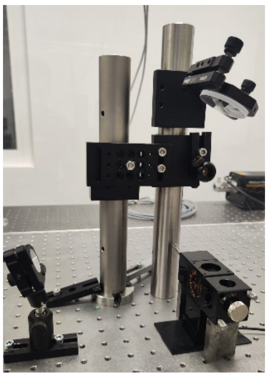

Fig. 2. Measurement setup - dielectric mirrors.

The system was enclosed in a PMMA (polymethyl methacrylate) shield to eliminate unwanted air currents and minimize temperature fluctuations during the measurement process.

System alignment was carried out using the maximum interferometric reading technique. Prior to alignment, the laser beam had to be positioned perpendicular, as close as possible, to axis of actuator motion.

Due to the small calibration range of the piezo actuator (maximum 100 µm), 1" optical posts and an optical iris were positioned at two locations, 200 mm apart, to facilitate coarse beam alignment. (Fig 3).

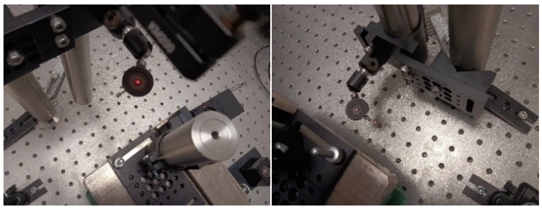

Fig. 3. System alignment.

The laser beam was initially aligned approximately perpendicularly to the surface of the optical table Satisfactory initial perpendicularity was achieved due to sufficient parallelism between the surfaces of the piezo actuator base and the retroreflector housing, facilitating efficient alignment by maximizing the interferometric signal.

To minimize the influence of the interferometer's dead path, the distance between the interferometer and the retroreflector was kept within 5 mm.

III. PRE-CALIBRATION TESTS

Prior to the start of the calibration procedure, the system's stability without motion was evaluated. The data acquisition frequency was set to 100 Hz, and stability was evaluated over a period of 60 seconds, corresponding to the calibration duration. The results of stability evaluation are presented in Fig. 4.

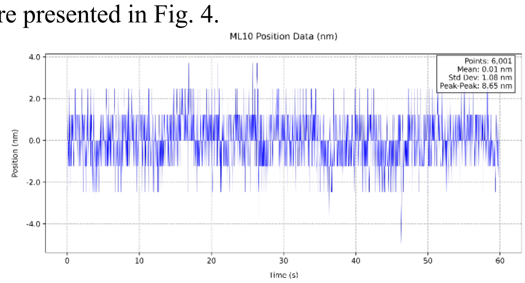

Fig. 4. System stability.

The stability results showed no indication of systematic trends, and the observed data variation was in line with expectations, resulting in a standard deviation of 1.08 nm.

Prior to the calibration procedure, discrepancy between the actuator's positive and negative displacement directions was tested. The results are presented in Fig. 5.

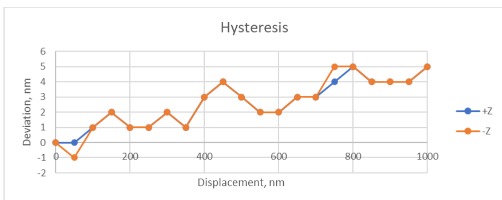

Fig. 5. Actuator displacement directions.

The results indicated no presence of hysteresis, i.e., no significant differences dependent on the direction of motion of the piezo actuator. However, it is recommended to verify the repeatability of the zero position to detect any unintended random displacements that may occur during the measurement process.

IV. CALIBRATION PROCEDURE AND RESULTS

The calibrated piezo actuator used in this study was the P-621.ZCD model by Physik Instrumente - a vertical nanopositioning stage capable of displacements of up to 100 µm, controlled via an integrated capacitive sensor. The actuator was driven by the E-625 Piezo Servo Controller, also produced by Physik Instrumente.

Although the actuator supports vertical displacements of up to 100 µm, calibration in this work was limited to a range of up to 1 µm, which was sufficient to meet the objectives of the HRZZ-IP-2024-05-3450 project.

Calibration was conducted from 0 to 1000 nm in 20 nm increments along the positive displacement direction. The measurement result is the arithmetic mean of three repeated measurements, with the total measurement time being under 60 seconds. The results are shown in Fig. 6.

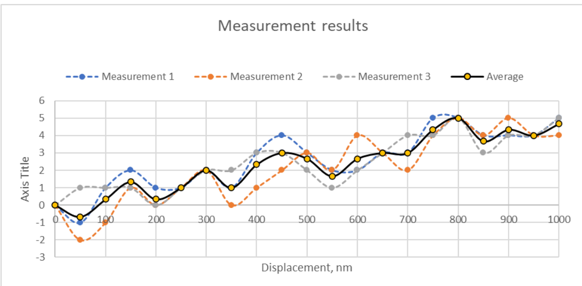

Fig. 6. Measurement results.

V. MEASUREMENT UNCERTAINTY

A comprehensive analysis of laser interferometry measurement uncertainty is provided in [3], where error sources are classified into three categories: instrumental, environmental, and geometrical errors of the measurement system.

Considering the measurement setup used in this study — and the fact that the actuator motion was calibrated only within a range of up to 1 µm—the relevant contributions to measurement uncertainty have been identified and analysed.

A. Geometrical errors

Due to the small calibration range of 1 µm, the estimation of the cosine error was performed using the preliminary laser beam alignment setup relative to the piezo actuator axis, as illustrated in Fig. 1. The distance between the two iris positions was 200 mm, with the maximum observed beam misalignment at the lower position did not exceed 1 mm.

Any potential tilt of the piezo actuator's surface relative to the displacement axis was eliminated using the method of maximum interferometer reading method.

In the worst-case scenario, the maximum deflection is calculated as:

$$\varphi = \arctan\left(\frac{1}{200}\right) = 0.286\,° \qquad (1)$$

and the cosine error is given by:

$$e_x = (1 - \cos(\varphi))L = 12.5 \cdot 10^{-6} \cdot L \qquad (2)$$

and for the maximum displacement of 1 µm, the error equals $e_x = 0.013$ nm.

Considering that alignment error may arise from both pitch and yaw, and assuming a rectangular distribution, the associated measurement uncertainty is quantified as follows:

$$u(e_x) = 0.013 \cdot \sqrt{\frac{2}{3}} = 0.011 \text{ nm} \qquad (3)$$

Given the setup used in this study, and the fact that actuator motion was calibrated only within a range of up to 1 µm, the influence of the Abbe offset is considered negligible.

B. Environmental errors

The ambient temperature was maintained within ±0.3 °C and humidity was regulated within ±15% RH. Air pressure was not controlled. During the measurement, environmental conditions were monitored using the EC10 environmental compensation unit. Automatic compensation was applied throughout the measurement process.

The overall compensation error budget, as specified in the calibration certificate, is 0.11 ppm at a reference temperature of 20 °C, which is negligible for a displacement of 1 µm.

The associated expanded uncertainty is u = 0.2 ppm, which is also considered negligible for a displacement of 1 µm. The measurement system was enclosed in a PMMA housing, and due to the short measurement duration (less than 60 seconds), no significant influence from optical drift is expected.

It is estimated that temperature variation during this period did not exceed ±0.01 °C, corresponding to a maximum displacement error of ±0.5 nm. Based on this estimation, and assuming a rectangular distribution, the uncertainty contribution due to optical drift was calculated as:

$$u(e_o) = 0.5/\sqrt{3} = 0.28 \text{ nm} \qquad (4)$$

To minimize dead path error, the interferometer and the zero-position were set at less than 5 mm apart (Fig. 7).

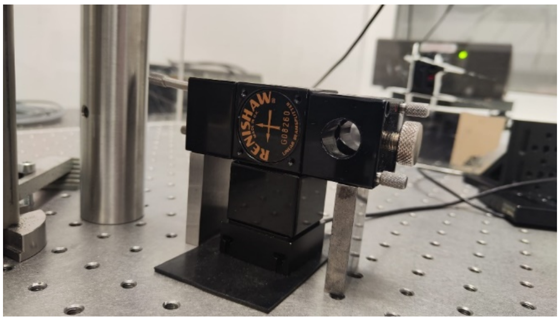

Fig. 7. Zero position.

Considering the maximum displacement of 1 µm, this effect can be considered negligible [3,4]. However, the dead path error depends more on the length of the dead path itself than on the actual measurement displacement. Although specific data for the Renishaw laser are not available, according to [5], the dead path error is estimated as ±0.14 ppm of the dead path distance. Accordingly, the associated uncertainty is:

$$u(e_{dp}) = \frac{0.7}{2} = 0.35 \text{ nm} \quad (5)$$

C. Instrumental errors

For the Renishaw ML10 laser interferometer, the deviation of the laser frequency from its nominal value - according to the calibration certificate - is 0.010 ppm, with a frequency stability of 0.015 ppm. Given the small calibration range of 1 µm, the impact of these frequency-related errors is considered negligible.

Optical nonlinearity was experimentally determined from the measurement data. In the worst-case scenario, it was estimated at ±1.5 nm. Given the sinusoidal nature of this error, a U-shaped distribution was assumed, and the corresponding uncertainty was calculated as:

$$u(e_{on}) = \frac{1.5}{\sqrt{2}} = 1.06 \text{ nm} \quad (6)$$

The resolution of the Renishaw interferometer is 1.24 nm, and the associated uncertainty is estimated as:

$$u(e_{res}) = \frac{1.24}{\sqrt{3}} = 0.72 \text{ nm} \quad (7)$$

The stability of the measurement system was evaluated over a 60-second period, which corresponds to the maximum calibration time. The results, presented in Figure 6, show an estimated standard deviation of 1.06 nm.

Since the calibration result was derived as the arithmetic mean of three independent measurements, the associated uncertainty is calculated as:

$$u(e_{st}) = \frac{1.06}{\sqrt{3}} = 0.62 \text{ nm} \quad (8)$$

The uncertainty budget, presented in Table 1, includes all relevant contributions that were identified and quantitatively evaluated.

Table 1. Uncertainty budget.

x_i	u_i	c_i	$u_i \cdot c_i$
e_x	0.011 nm	1	0.011 nm
e_o	0.28 nm	1	0.28 nm
e_{dp}	0.35 nm	1	0.35 nm
e_{on}	1.06 nm	1	1.06 nm
e_{res}	0.72 nm	1	0.72 nm
e_{st}	0.62 nm	1	0.62 nm
			$u_c =$ 1.49 nm
			$U =$ 3.0 nm, $k = 2$, $P = 95$ %

where:
e_x - cosine error
e_o - environmental errors
e_{dp} - dead path error
e_{on} - optics nonlinearity
e_{res} - interferometer resolution
e_{st} - measurement system stability

VI. CONCLUSION

Accurate displacement measurement plays an important role in numerous high-precision applications. Therefore, reliable and traceable calibration of displacement actuators is essential.

Only a small number of national metrology institutes have established calibration setups for piezoelectric actuators, with even fewer that provides this calibration service in the BIPM KCDB database.

For this reason, a custom setup for calibrating piezo actuator was developed at the Croatian National Laboratory for Length, using a Renishaw ML10 laser system. A dedicated alignment procedure was designed, and a thermal cover was constructed to ensure stable metrological conditions. Prior to the calibration procedure, system stability was tested under static conditions. The stability results showed no indication of systematic trends, and the observed data variation was consistent with expectations, yielding a standard deviation of 1.08 nm.

In addition, bi-directional testing was performed, confirming the absence of hysteresis. Once the system's stability was verified, the calibration procedure was carried out.

The calibrated piezo actuator used in this study was the P-621.ZCD model, a vertical nanopositioning stage capable of displacements up to 100 µm. However, the calibration was limited to a range of up to 1 µm, in 20 nm increments along the positive displacement direction, which was sufficient to meet the objectives of the HRZZ-IP-2024-05-3450 project.

The measurement result was obtained as the arithmetic mean of three repeated measurements, with the total measurement time kept under 60 seconds. The calibration results indicate the presence of a linear error, with a maximum deviation within the 1 µm calibration range not exceeding 5 nm.

All relevant contributions to the measurement uncertainty are presented in this paper. The expanded measurement uncertainty of the actuator calibration has been estimated at 3.0 nm.

Future research will focus on implementing 90° optical square to minimize the overall laser path. In addition, the calibration range of the actuator will be extended up to 100 µm, and the results will be verified by comparison with the calibration results obtained at a laboratory with relevant CMC listed in the BIPM KCDB database.

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