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# Characterization of 2D angular actuators to the nanoradian level

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**Abstract**

We present an instrument designed and built to the purpose of characterizing precision angular actuators with a resolution surpassing the best devices on the market. The noise of the device is better than 1 nrad/√Hz in the band from 0.1 Hz to 10 kHz on two orthogonal axes. We synthetically describe the working principle, the practical realization and the case study on a top-level commercial angular actuator.

Calibration, angle metrology, piezo actuator, nanoradiant

## 1. Introduction

Angular actuators are one of the key tools for precision manufacturing, inspection and research activity. Today are present on the market precision angular actuators able to tilt objects (e.g. a steering mirror) in one or two directions (1D or 2D) with exceptional precision. Most of these actuators are piezo driven and have integrated precision metrology such as strain gauges, optical encoders and capacitive sensors. The nominal resolution of these devices is as low as the nanoradian level, but the accuracy of the scale need to be calibrated and the real resolution must be verified. Finally, in some applications the time response must be characterized up to the kilohertz range. No commercial instruments are today available to characterize these devices with the wanted band, resolution and accuracy. We present an instrument designed and built to the purpose capable of characterizing angular actuators with a resolution surpassing the best device on the market. The resolution of the device is better than 1 nrad/√Hz in the band from 0.1 Hz to 10 kHz on two orthogonal axes. Here we describe the working principle, the practical realization and the case study on a top-level commercial angular actuator.

## 2. Working principle

The measurement principle combines the effect of the optical lever (which converts a rotation of a mirror into a translation of a laser beam) and the reflection law (the rotation of the reflected beam is twice the rotation of the mirror), in a multiple reflection set-up. The principle has been used as an high resolution autocollimator and described in [1]. A laser beam is sent towards a pair of quasi-parallel mirrors (see figure 1) and after *N* reflections exits from the same direction (solid line). Mirror A is glued to the tilting device to be measured while mirror B is kept fixed. When mirror A is rotated, the exiting mirror is rotated and translated proportionally to the distance between the two mirrors and *N* (dashed line). By using special mirrors and proper angles, *N* can be around 70 or more leading to an enormous gain. A position sensitive detector measures the displacement of the output laser beam and converts it into an electric signal. The sensitivity of the device is better than $10^{-11}$ rad/√Hz.

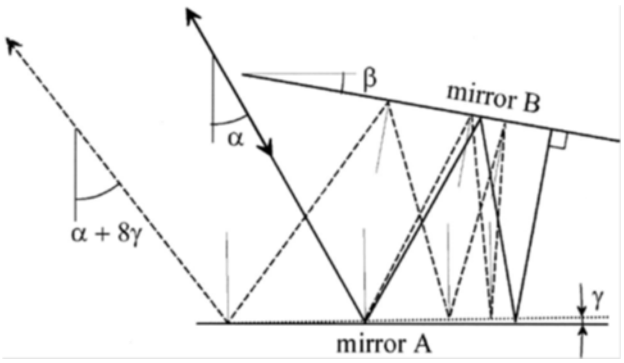


**Figure 1.** Ray tracing of the multiple reflection set-up showing the effect of the counterclockwise rotation of mirror A on the reflected beam.

## 3. Experimental set-up

The picture of figure 2 depicts the experimental set-up. The key elements are highlighted in the picture. The laser beam is provided by a fiber coupled stabilized He-Ne laser. The collimated beam is reflected between the two mirrors and finally reaches a position sensitive detector (PSD). A polarizer is used to adjust the optical power on the PSD. The fixed "reference" mirror, is mounted on a tip tilt optical mount driven by two motorized screws (Picomotor, New Focus, USA).

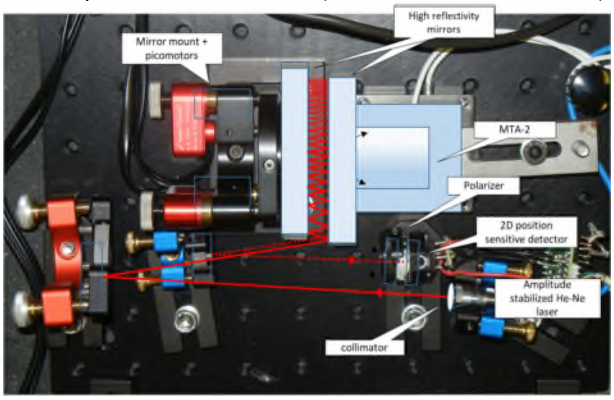


**Figure 2.** Picture of the experimental set-up

The motorized screws are used to adjust the angle between the mirrors before the measurement set, and are switched off during the measurement. In the experiment here shown we have tested the nano actuator Nano-MTA2 produced by MadCityLabs (USA) capable of 2 mrad p.p. full scale on two orthogonal axis. The MTA-2 is equipped with integrated metrological "picoQ" sensors with a nominal resolution of 4 nrad and a bandwidth of 400 Hz.

## 4. Results

We have performed two kinds of measurements: the first is to characterize the noise of the calibration device and of the device under test (DUT) in the frequency domain; the second is to characterize the resolution of the device under test in the time domain. All the measurements have been done for both vertical and horizontal axes of the DUT. In the following, only the esults of the horizontal axis are shown.

In figure 3 are summarized the results of the noise tests. The whole experiment was mounted on a stable granite table (passively isolated) and enclosed in a wooden box to isolate for acoustic noises and air turbulences. The signals coming from the PSD are amplified and sent to a 16 bit 100 kS/s A/D converter and processed by a LabView based software to calculate the noise spectral density. The green curve represent the noise limit due to the laser noise, the detector noise and the electronics noise. It has been obtained sending the laser beam on the detector after only one reflection. The blue curve is the noise spectral density of the sensor when the DUT is switched off. The noise is limited by the environmental disturbances (mainly mechanical vibrations) coupled to the mechanical structure. The dashed red line indicates the 1 nrad/√Hz level. The performances could be further ameliorated by a better acoustic and vibration isolation. Finally the DUT is switched on. The result of the measurement is the red curve. The difference between the blue and the red curves show that we are measuring the "real" noise performance of the actuator, that in this case is basically due to the noise of the active control system.

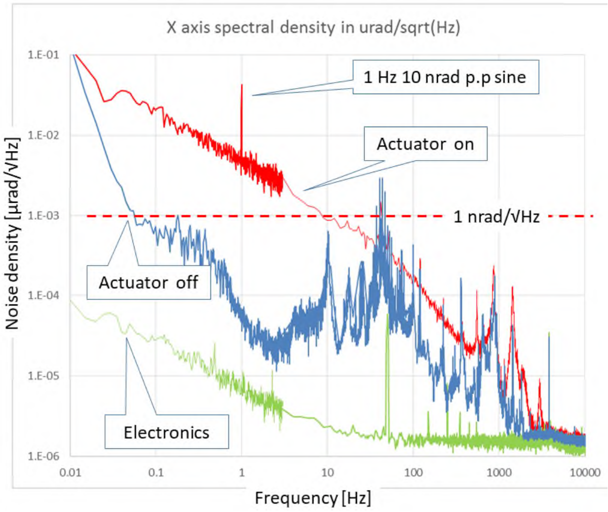


**Figure 3.** Noise spectral density curves of the output signal of the measuring device. The meaning of the three curves is explained in the text.

In figure 4 are summarized the results of the resolution tests. A small signal is sent to the MTA-2 to drive the actuator with a square angular signal having nominal amplitude of 25 nrad p.p. at 1 Hz. The blue and red curves are the output of the calibration device low pass filtered respectively at 10 kHz and 1 kHz showing the "real" behaviour of the DUT. The green, purple and turquoise curves are the output of the Nano-MTA2 sensor low pass filtered respectively at 30 Hz, 1 kHz and 10 kHz. It is evident that the output of the integrated metrology of the actuator underestimates the real noise of the same, since is a measurement taken "in the control loop". Nevertheless the exceptionally good resolution of the actuator under test is definitively demonstrated with this experiment.

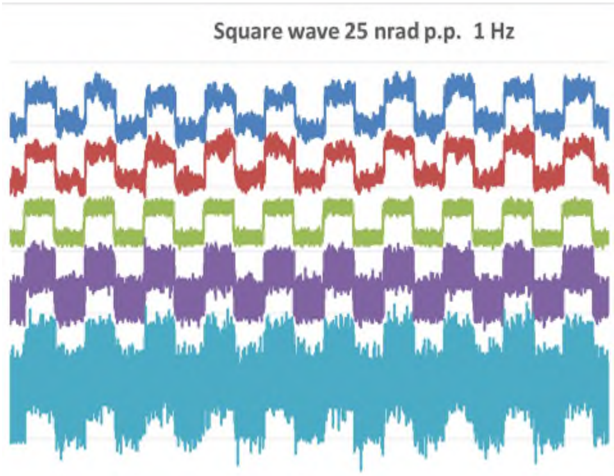


**Figure 4.** Time domain characterization of the MTA-2. The meaning of the various tracks is explained in the text.

Finally to complete the characterization we have performed a calibration of the DUT on the full scale to check for the scale factor and linearity of the same. The calibration has been undertaken by direct comparison with a reference autocollimator (ELCOMAT HR by Moeller-Wedel, Germany), in turn calibrated against the INRIM angle standard [2].

## 5. Conclusions

We have realized a simple and effective set-up used to calibrate and characterize precision piezoelectric nano-angle actuators. The noise of the device (limited by environmental disturbances to less than 1 nrad/√Hz for frequencies higher than 0.1 Hz) is lower than the best actuators available on the market and the frequency range (over 10 kHz) exceedes the actuator bandwidth. With a practical experiment we have demonstrated the feasibility of the calibration of a top performance commercial device. The traceability is guaranteed through the use of a reference autocollimator calibrated against the INRIM angular standard.

## References


[1] Pisani M, Astrua M, "Angle amplification for nanoradian measurements," Appl. Opt. **45** (2006) 1725-1729

[2] Pisani M, Astrua M, "The new INRIM rotating encoder angle comparator (REAC)" Meas. Sci. Technol. **28** (2017) 045008