Optical rotating torque sensor with nano newton-meter resolution based on a hanging torsion wire

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Introduction

There is a lack of readily-available solutions to measure or apply torques in the nano newton-meter (10^{-9} Nm) range:

- The most sensitive commercial instruments are limited to applications in the micro newton-meter (10^{-6} Nm) range (Lecureux Kuiper or ATI nano17).
- Known devices with a sensitivity in the nano newton-meter range are based on complex MEMS that are not commercially available, necessitate advanced fabrication processes, and need adaptation to operate as actuators.

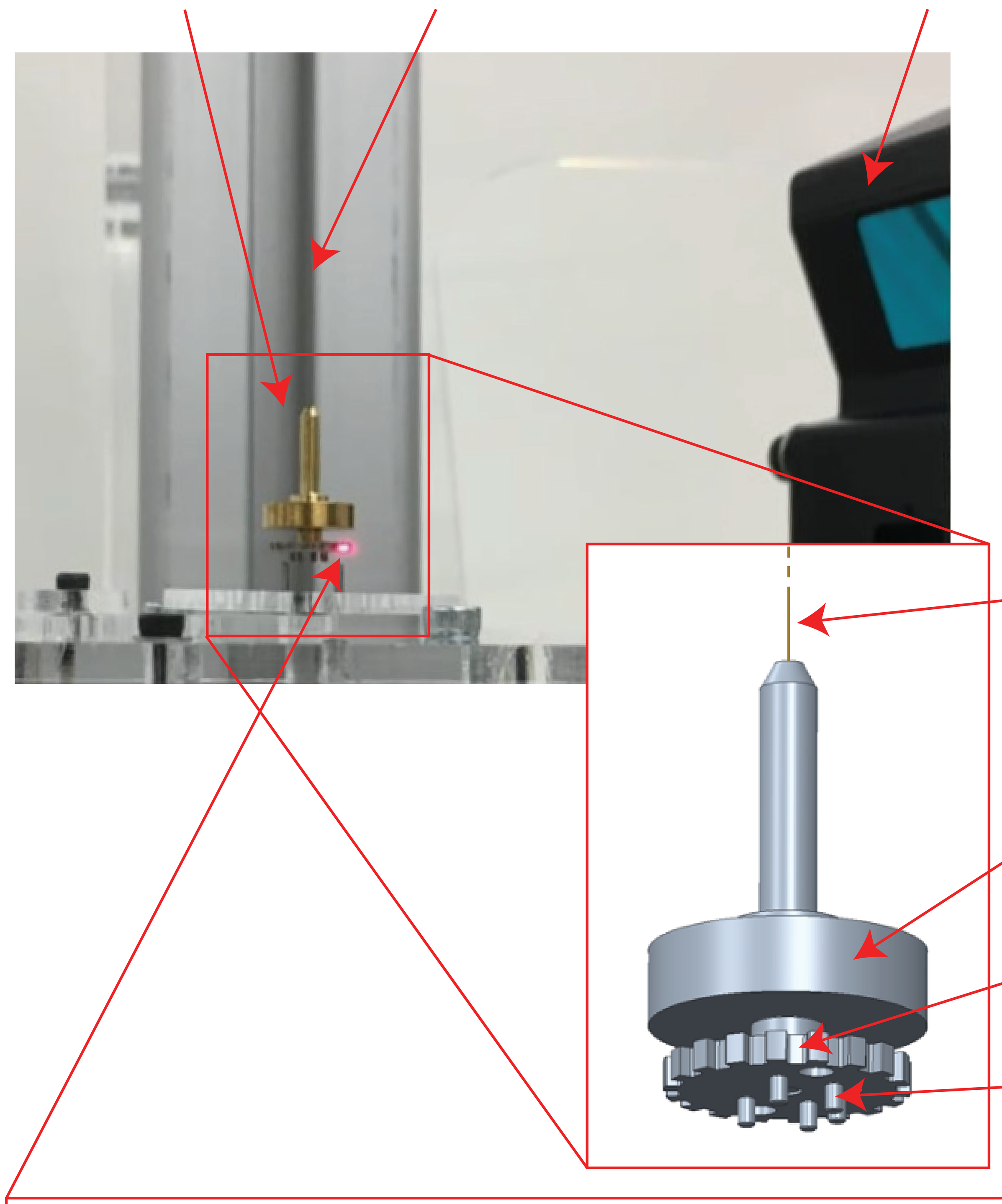
We present a novel torque measuring setup working in the nano newton-meter (10^{-9} Nm) range. The setup can be used to measure torques in static and rotating modes. The central novelty is a long (1 meter range) thin (diameter of a few tens of micrometers) metallic wire used instead of the relatively stiff torsion zone of the shaft of classical rotating torque sensors. This thin wire is made straight by placing it vertically and suspending a mass at its lower extremity. The very low torsional stiffness of the wire is determined by measuring the frequency of the torsional pendulum constituted by the wire and its hanging mass.

Experimental Setup

The experimental setup consists of a mass suspended by a torsion wire. The mass is coupled to the rotating crank whose torque is to be measured via a pair of interface pins transmitting the couple. The contact between the pin and crank via two contact points is such that a pure torque is transmitted, without overconstraints. The torque value is derived from the torsion angle of the suspension wire, knowing its torsional stiffness. The setup has two configurations.

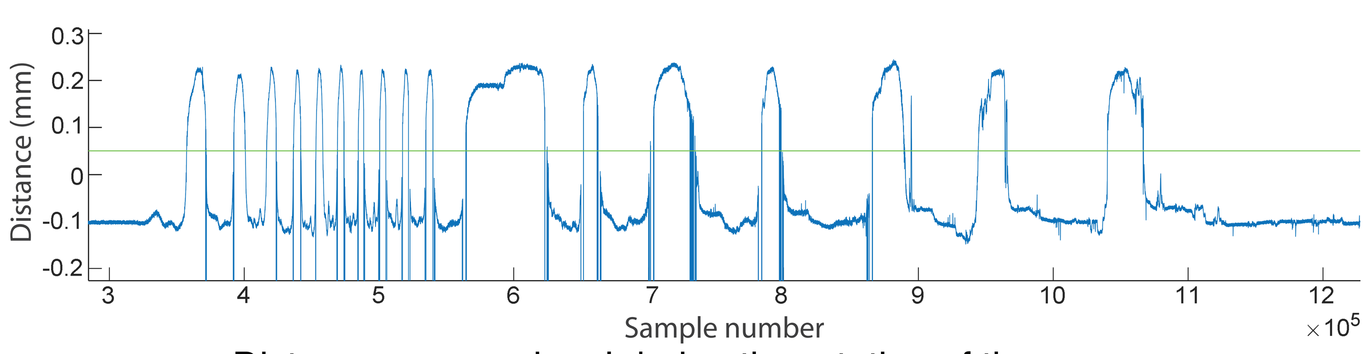
A. **Static torque sensor**: the upper extremity of the wire is attached to a fixed gantry and the torsion angle is determined by measuring the rotation of the suspended mass.

B. **Rotating torque sensor**: the upper extremity of the wire is attached coaxially to the shaft of a servomotor whose angular position is controlled so as to maintain a given angular offset with the suspended mass and hence continuously controlling the applied torque.



Torsion angle measurement

The angular position of the suspended mass is measured using a laser distance sensor pointed towards radial grooves machined in the suspended mass. These grooves have a periodic angular spacing of 20 degrees. The signal returned by the distance sensor as the mass rotates is processed to detect the edges of the grooves and the angular position is reconstructed incrementally. The principle is similar to that of the widely-used incremental optical encoder.



Distance sensor signal during the rotation of the mass

Measurement resolution

With a torsional stiffness k_0 = 9.82 nN·m/rad = 61.7 nN·m/turn and an angular resolution α_r=10°, the resulting torque resolution of the setup is

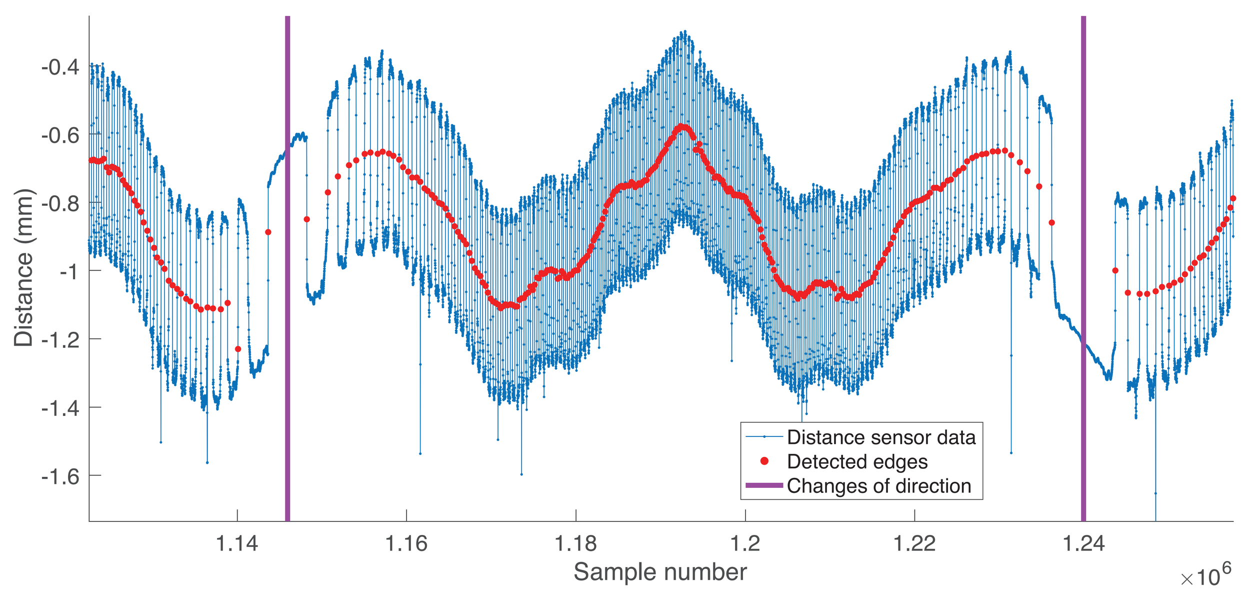
$$R = k_0\,\alpha_r = 1.71 \text{ nN·m}.$$

For the range of torques considered for this sensor (<1 μN·m), this resolution is the limiting factor to the accuracy of the setup. Indeed, in this range the uncertainty on the measured stiffness (±0.01 nN·m/rad) results in an absolute torque uncertainty below 1.02 nN·m.

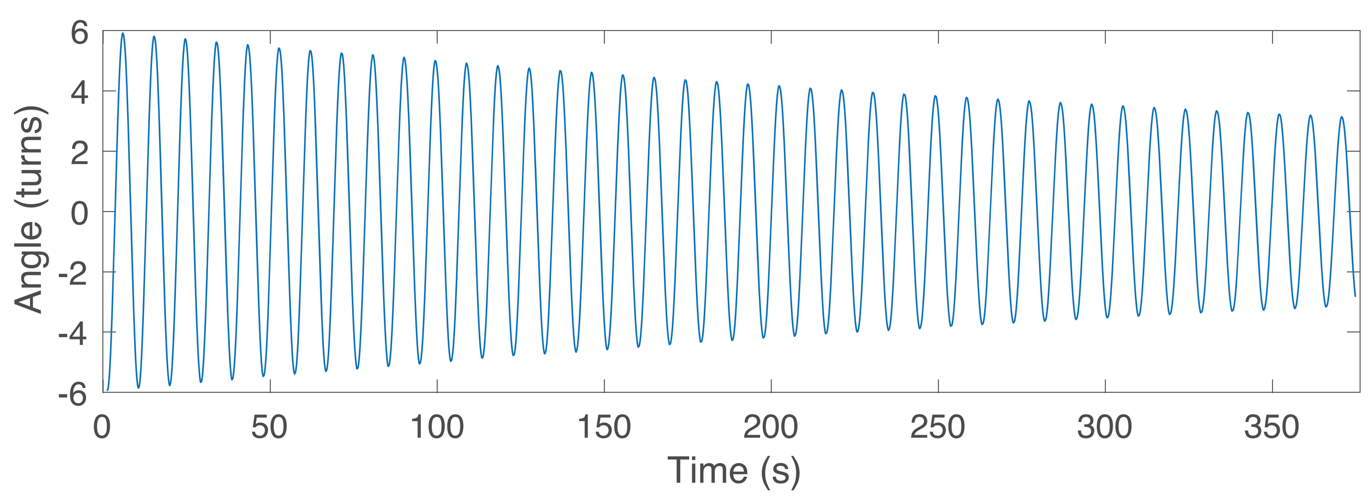
Torsion wire stiffness characterization

Knowing the moment of inertia of the suspended mass about the wire axis (J=21.8 g·mm²), the torsional stiffness of the wire was derived from the frequency of the system when it oscillates in torsion pendulum mode.

1. Distance sensor measurement in free torsion pendulum oscillation

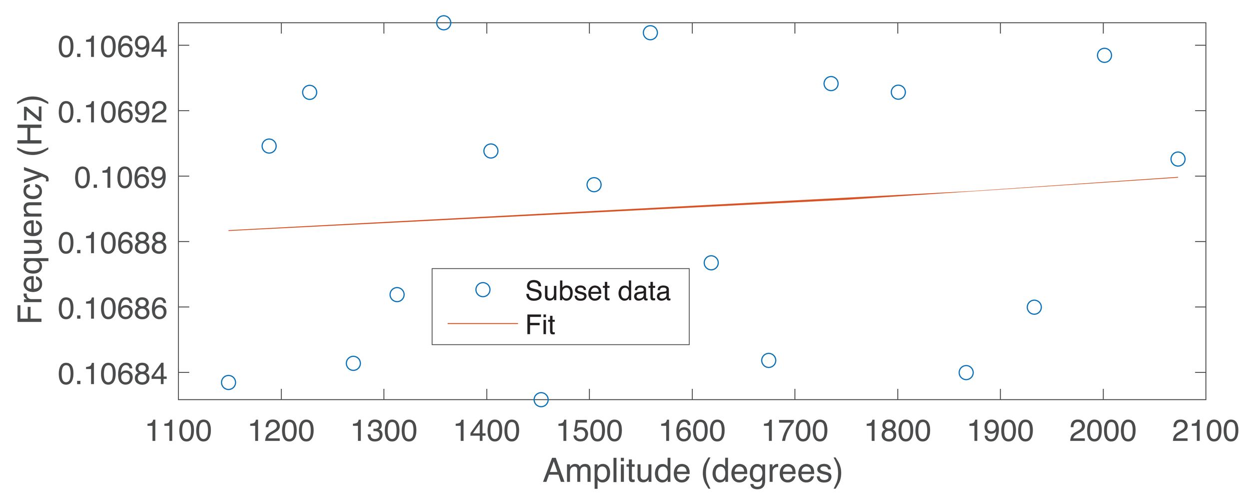


2. Reconstructed angular position vs time of the torsion pendulum



3. Extracted frequency-amplitude characteristic of the torsion pendulum

This plot was obtained by fitting sinusoidal functions to subsets of the angular position versus time data.



The nonlinear stiffness coefficients were derived from the coefficients of a second order even polynomial fit of the frequency-amplitude characteristic: $\omega(\theta) = \omega_0 + \omega^2\,\theta^2$, yielding the nonlinear restoring torque

$$M = k_0\,\theta + k_2\,\theta^3 = 9.82\,\theta + 0.44\cdot 10^{-5}\,\theta^3$$

Since the estimated nonlinear term k_2 would result in less than 0.4% stiffness increase for 6 turns (which is more than the requirements of our application), it is reasonable to neglect it and assume a purely constant stiffness k_0.

Example of application on a mechanical watch gear train

The performance of this setup has been demonstrated by measuring the output torque of a modified mechanical watch gear train constituted of two 10:1 speed multiplying stages in series driven by a commercial torque meter.

With outputs torques ranging from $40\cdot 10^{-9}$ to $160\cdot 10^{-9}$ Nm, the measurements showed a linear input to output torque ratio of 108, for a total gear ratio of 100:1, corresponding to a load-dependent efficiency of 92.6%. Constant losses of 7.63 nN·m were also estimated.