Ultrasensitive and universal vectorial force-field sensor

Due to their ultralow mass, nanometre-scale mechanical oscillators can be used to convert a very weak force into a measurable displacement. By measuring the vibrations of a long, cylindrical, nanowire oscillator, and recording their modifications as the nanowire is scanned through a force field (e.g., an electrostatic field), one can measure and map the variations of the magnitude and direction of the force field with attonewton ($10^{-18}$ N) precision. Lateral force-field gradients couple the nanowire’s two transverse eigenmodes, i.e. the transverse modes of oscillation in two perpendicular directions, causing frequency shifts and rotation of the eigenmode basis. Also, rotational force fields can break the orthogonality between these two eigenmodes. The nanowire dynamics is strongly altered, thus modifying the fundamental relation which connects the mechanical susceptibility and the noise correlations of the system, and giving rise to a new fluctuation-dissipation relation.

At the Institut NÉEL, we have developed an experiment aiming at measuring the vectorial structure of force fields exerted on the vibrating extremity of a 70 micron long silicon carbide nanowire, of 200 nm diameter. This nanowire oscillates at a frequency around 70 kHz. Its two fundamental transverse eigenmodes vibrate along perpendicular orientations with quasi identical eigenfrequencies (within 1%). These lateral vibrations are read out optically using a tightly focused laser beam, allowing in particular to resolve the thermal noise or Brownian motion of both eigenmodes.

The eigenmodes of the nanomechanical oscillator are modified when it is immersed in an external force field presenting spatial variations (Fig. 1). Divergence-like force fields generate frequency shifts, while shear or rotational force fields cross-couple both eigenmodes and cause a rotation of the eigenmodes’ orientations. By measuring those modifications of the nanowire’s vibration properties, we can determine the local lateral force-field gradients exerted on the nanowire. Thus, the nanowire acts as a “nano-compass” (Fig. 2). It tends to orientate the axes of its eigenmodes along the eigendirections of the force field under investigation, which can subsequently be reconstructed and mapped spatially. The sensitivity demonstrated is impressive: Force gradients of a few nN/m could be observed, corresponding to force variations of a few attonewtons over the nanometer-sized spatial spreading of the nanowire’s random thermal motion.

Our measurement technique allows us to identify the shear components of the force field, which cannot be resolved with standard uniaxial force probes. In particular, we can explore the rotational optical force fields produced in sharply focused laser beams. Such non-conservative force fields cause a non-reciprocal coupling between the two eigenmodes and are responsible for a breaking of their orthogonality: Their orientations tend to move towards each other. By combining response measurements and thermal noise analysis, we could demonstrate a violation of the fluctuation-dissipation relation which connects the thermal noise spectrum to the imaginary part of the nanowire mechanical susceptibility. The origin of the deviation arises from the out of equilibrium state of the system induced by rotational force fields.

The theoretical model we developed explains all observed signatures, including the observed excess of thermal noise and enhanced mechanical response of the system, and has allowed us to formulate a patch to the fluctuation-dissipation relation that remains valid in the presence of non-conservative force fields. Further developments will consist in speeding up the measurement process by analyzing trajectories driven by calibrated forces instead of by random thermal motion. This novel, universal, ultra-high sensitivity measurement apparatus provides vectorial information about the forces exerted on a nanometric probe, providing a new way for exploring proximity, magnetic, or optical force-landscapes.

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FURTHER READING...
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