Journal Club: Measurement-based control of a mechanical oscillator at its thermal decoherence rate

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LETTER

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Measurement-based control of a mechanical oscillator at its thermal decoherence rate

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In real-time quantum feedback protocols[1,2], the record of a continuous measurement is used to stabilize a desired quantum state. Recent years have seen successful applications of these protocols in a variety of well-isolated micro-systems, including microwave photons[3] and superconducting qubits[4]. However, stabilizing the quantum state of a tangibly massive object, such as a mechanical oscillator, remains very challenging: the main obstacle is environmental decoherence, which places stringent requirements on the timescale in which the state must be measured. Here we describe a position sensor that is capable of resolving the zero-point motion of a solid-state, 4.3-megahertz nanomechanical oscillator in the timescale of its thermal decoherence, a basic requirement for real-time (Markovian) quantum feedback control tasks, such as ground-state preparation. The sensor is based on evanescent optomechanical coupling to a high-Q microcavity[5], and achieves an imprecision four orders of magnitude below that at the standard quantum limit for a weak continuous position measurement[6]—a 100-fold improvement over previous reports[7–9]—while maintaining an imprecision–back-action product that is within a factor of five of the Heisenberg uncertainty limit. As a demonstration of its utility, we use the measurement as an error signal with which to feedback cool the oscillator. Using radiation pressure as an actuator, the oscillator is cold damped[10] with high efficiency: from a cryogenic-bath temperature of 4.4 kelvin to an effective value of 1.1 ± 0.1 millikelvin, corresponding to a mean phonon number of 5.3 ± 0.6 (that is, a ground-state probability of 16 per cent). Our results set a new benchmark for the performance of a linear position sensor, and signal the emergence of mechanical oscillators as practical subjects for measurement-based quantum control.

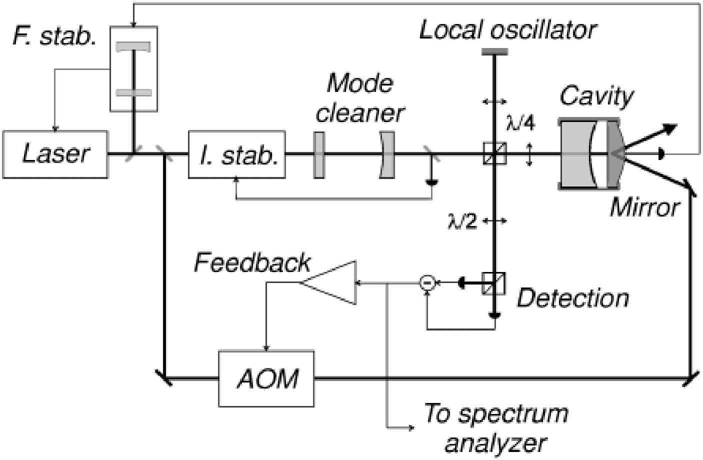
anical oscillator undergoing thermal Brownian motion is steered towards its ground state by minimizing a measurement of its displacement, S_x (here expressed as a power spectral density[6] evaluated at the mechanical oscillator frequency, Ω_m). A conventional strategy[10] is to apply a feedback force proportional to the time derivative of the measurement (which estimates the velocity of the oscillator). The resultant damping acts to reduce (cool) the motion of the oscillator until it coincides with the measurement imprecision, S_x^imp. Cooling the oscillator until it spends most of the time in its ground state (a mean phonon occupancy of $n_\mathrm{m} < 1$) is possible if S_x^imp remains lower than the zero-point fluctuations of the damped oscillator, that is, if $S_x^\mathrm{imp} \lesssim S_x^\mathrm{zp}/n_\mathrm{th}$ (see Supplementary Information), where S_x^zp is the spectral density of intrinsic (absent feedback) zero-point fluctuations and n_th is the phonon occupancy of the thermal bath. ($S_x^\mathrm{zp} = 4x_\mathrm{zp}^2/\Gamma_\mathrm{m}$ is proportional to the ratio of the ground-state variance $x_\mathrm{zp}^2 = \hbar/(2m\Omega_\mathrm{m})$ and the intrinsic mechanical damping rate Γ_m, where $\hbar$ is the reduced Planck's constant and m is the effective mass of the oscillator.) In the frequency domain, this condition on S_x^imp amounts to resolving the intrinsic thermal displacement $S_x \approx 2n_\mathrm{th}S_x^\mathrm{zp}$ with a signal-to-noise ratio of $S_x/S_x^\mathrm{imp} \gtrsim 2n_\mathrm{th}^2$; in the time domain, it corresponds to resolving the zero-point motion at a characteristic 'measurement' rate[6]

$$\Gamma_\mathrm{meas} \equiv \frac{x_\mathrm{zp}^2}{2S_x^\mathrm{imp}} \gtrsim \frac{\Gamma_\mathrm{th}}{8} \qquad (1)$$

where $\Gamma_\mathrm{th} \approx \Gamma_\mathrm{m} n_\mathrm{th}$ is the thermal decoherence rate of the oscillator. Equation (1) implies the ability to resolve a displacement of x_zp in the timescale over which a single phonon enters from the thermal bath, Γ_th^{-1}. Satisfying this requirement is a technically daunting challenge

Cooling of a Mirror by Radiation Pressure

P. F. Cohadon, A. Heidmann, and M. Pinard, Phys. Rev. Lett. **83**, 3174 (1999).



Cooling of a Mirror by Radiation Pressure

Fourier transform of mirror displacement at frequency Ω is proportional to applied forces

$$\delta x(\Omega) = \chi(\Omega)[F_T + F_{\mathrm{rad}}(\Omega)]$$

where

$$\chi(\Omega) = \frac{1}{M(\Omega_M^2 - \Omega^2 - \mathrm{i}\Gamma\Omega)}$$

is the mechanical susceptibility.

Radiation pressure is proportional to the speed $v = \mathrm{i}\Omega\delta x$ of the mirror

$$F_{\mathrm{rad}}(\Omega) = \mathrm{i}M\Omega g\delta x(\Omega)$$

The resulting motion

$$\delta x(\Omega) = \frac{1}{M(\Omega_M^2 - \Omega^2 - \mathrm{i}(\Gamma + g)\Omega)} F_T$$

What we omitted?

We have ignored quantum back-action force due to the radiation presure shot noise.

Introduction to quantum noise, measurement, and amplification

A. A. Clerk, M. H. Devoret, S. M. Girvin, F. Marquardt, and R. J. Schoelkopf, Rev. Mod. Phys. **82**, 1155 (2010).

- We assume that the coupling is small enough that the phase shifts are always very small and hence the measurement is weak.
- Many photons will have to pass through the cavity before much information is gained about the value of the phase shift and hence the value of x
- This not a projective measurement

Quantum limit on the measurement noise

- Quantum limit on the measurement noise

$$\sqrt{S_{FF} S_{xx}} = \hbar/2$$

- Follows from Heisenberg's uncertainty principle

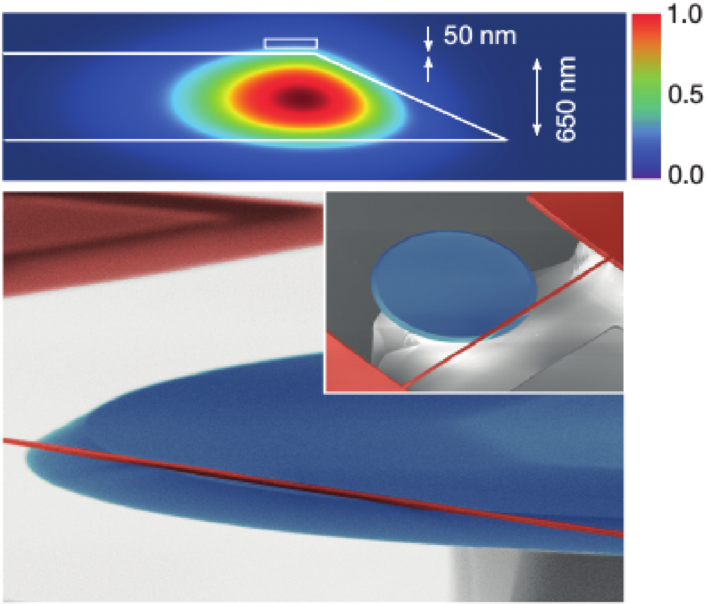
Quantum limit on weak continuous position detection

- For oscillator the position does not commute with the Hamiltonian
- Total noise added by the measurement

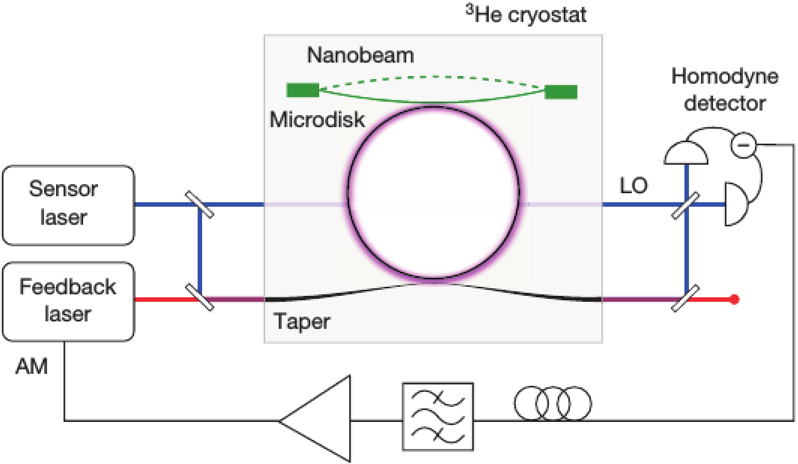
$$\bar{S}_{xx,\mathrm{add}}(\Omega_M) = |\chi(\Omega_M)|^2 S_{FF} + \frac{\hbar^2}{4}\frac{1}{S_{FF}}$$

- Minimum uncertainty of the measurement is two times larger than the ground state uncertainty
- This is known as standard quantum limit
- Feedback counteracts back-action!

Near-field optomechanical transducer



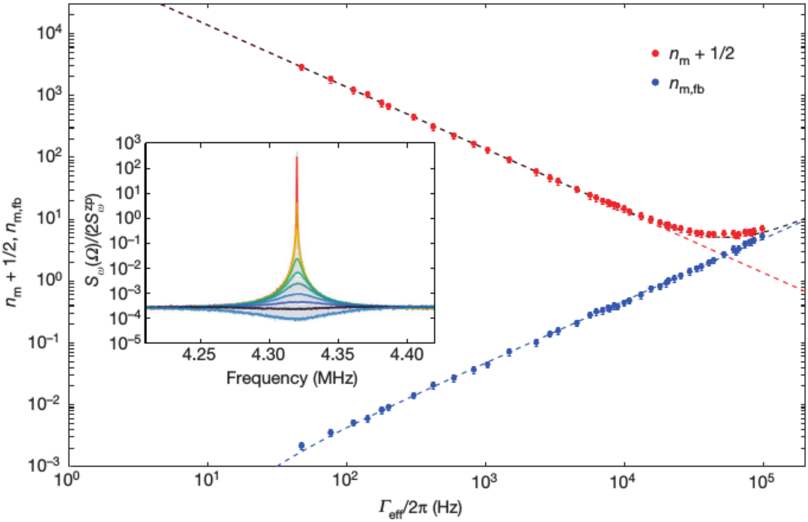
Measuring and controlling the position of a nanomechanical beam



Parameters

- $65\,\mu\mathrm{m} \times 400\,\mathrm{nm} \times 70\,\mathrm{nm}$ (effective mass $m < 2.9\,\mathrm{pg}$) nanobeam placed approximately $50\,\mathrm{nm}$ from the surface of a microdisk with a diameter of $30\,\mu\mathrm{m}$.
- For the mechanical oscillator, the $\Omega_M \approx 2\pi \times 4.3\,\mathrm{MHz}$ fundamental out-of-plane mode of the nano-beam is used
- Two optical modes: a "sensor" mode at $\lambda_c \approx 775\,\mathrm{nm}$ and a "feedback" mode at $\lambda_c \approx 843\,\mathrm{nm}$

Radiation-pressure feedback cooling to near the ground state



Summary

Results establish new benchmarks for the linear measurement and control of a mechanical oscillator. Using an optomechanical sensor with a readout imprecision that is nearly 40 dB below that at the SQL, we have shown that traditional radiation pressure cold-damping can be used to cool a nanomechanical oscillator to a mean phonon occupancy of approximately 5.3.

Thank you for your attention!