Back-action Evading Impulse Measurement with Mechanical Quantum Sensors

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Abstract

The quantum measurement of any observable naturally leads to noise added by the act of measurement. Here, we develop a measurement protocol building on the pioneering work by the gravitational wave community [1,2] which allows for reduction of added noise from measurement by coupling an optical field to the momentum of a small mirror. As a specific implementation, we present a continuous measurement protocol using a double-ring optomechanical cavity. We demonstrate that with experimentally relevant parameters, this protocol can lead to significant back-action noise evasion, yielding measurement noise below the standard quantum limit over many decades of frequency [3].

Introduction

- Optomechanical Hamiltonian: Consider an optical cavity mode $(a, a^\dagger)$ and a mechanical oscillator (x, p) coupled by radiation pressure [4].

$$H_{\text{int}} = \hbar \frac{\partial w_{cav}}{\partial x_{eq}} x\, a^\dagger a \xrightarrow{\text{strong optical drive, } \alpha} \hbar \frac{\partial w_{cav}}{\partial x_{eq}} \alpha^2 x + \hbar G x (a + a^\dagger)$$

- In the linearized regime, the mechanical position is written out on the optical phase quadrature.

Noise sources:

- Irreducible noise floor – coupling of the measurement device with its environment
- Reducible noise floor – measurement added noise (depends on how we probe the system); This can be reduced with choice of measurement protocol.
    - Shot noise – from statistical counting error of photons
    - Backaction noise – from fluctuations in the radiation pressure of light with which we probe the mechanics

[1] V. Braginsky and F. J. Khalili, Physics Letters A 147, 251 (1990)

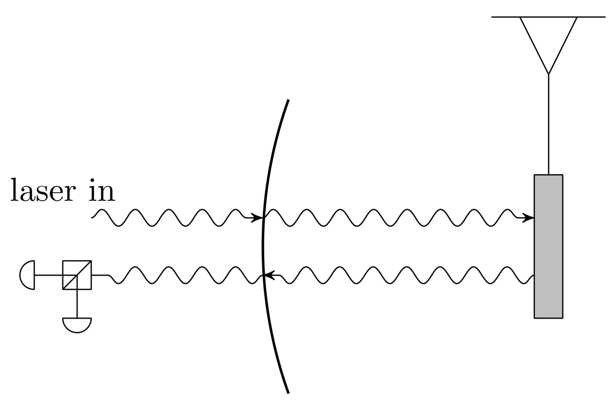
[2] Danilishin et al. Light: Science & Applications (2018)

[3] S. Ghosh, D. Carney, P. Shawhan and J. M. Taylor, (2019) arXiv:1910.11892

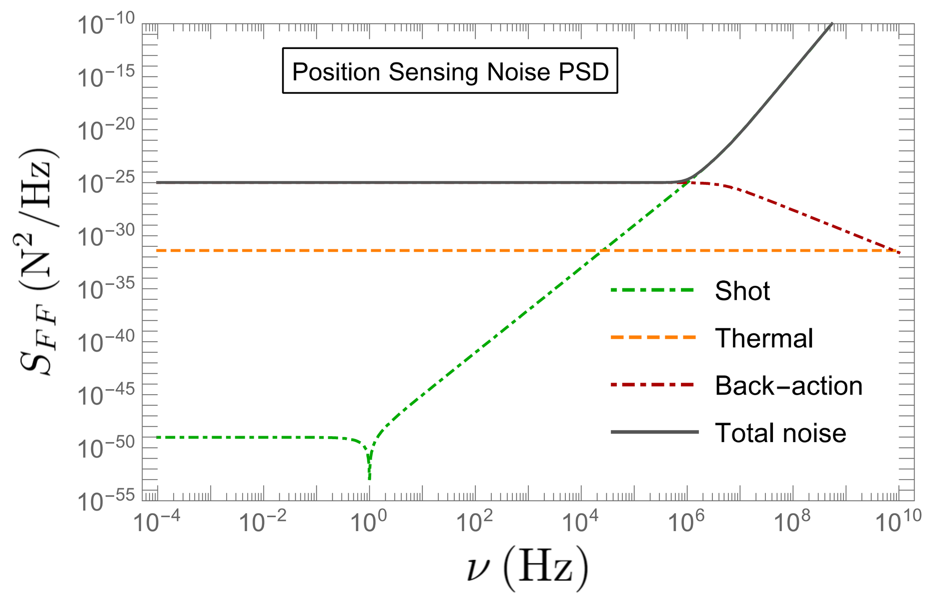
[4] A. A. Clerk, M. H. Devoret, S. M. Girvin, F. Marquardt, and R. J. Schoelkopf, Rev. Mod. Phys. 82, 1155 (2010)

[5] D. Carney, S. Ghosh, G. Krnjaic, and J. M. Taylor, (2019) arXiv:1903.00492

Continuous Position Measurement



- The standard position measurement protocol is described with a single sided optomechanical system [4].

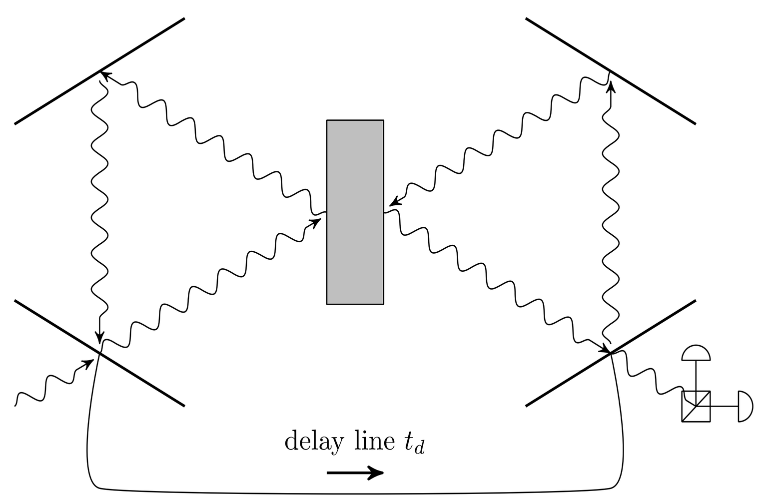


- The estimated power spectral density of the force acting on the mechanics and the impulse variance for this setup are given below.

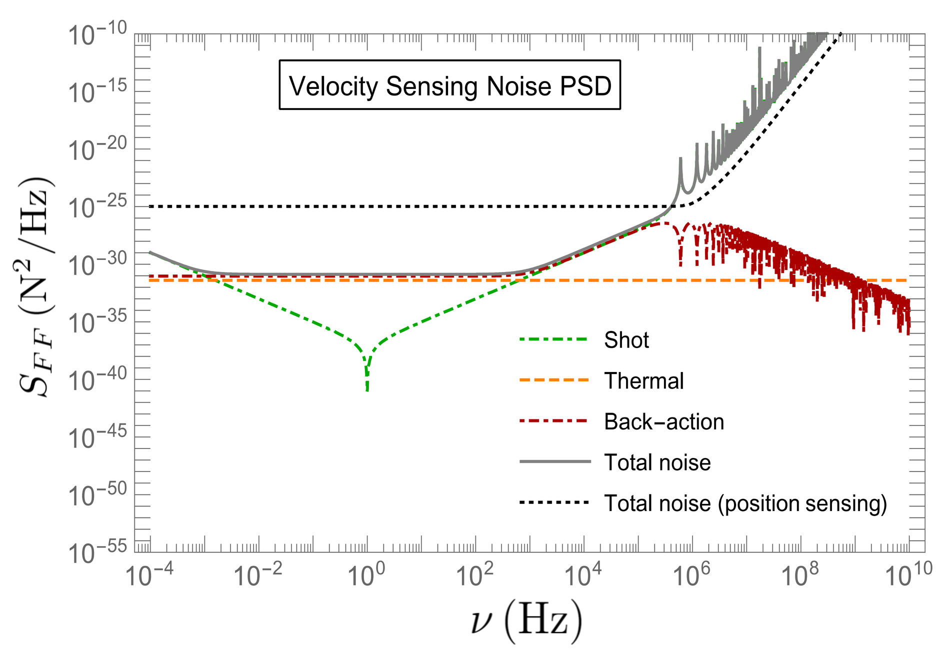
$$N(\nu) = \frac{1}{\kappa|G|^2|\chi_c|^2|\chi_m|^2} + N_{BM} + \hbar^2|G|^2\kappa|\chi_c|^2$$

$$\Delta p^2_{\text{noise}} = N_{BM}\tau + \frac{\hbar m}{\tau} = N_{BM}\tau(1+\eta^2)$$

Continuous Momentum Measurement



- Two ring cavities share a common mechanical element (a two-sided mirror) and are coupled by a delay line with loss probability L.
- The light interacts with the shared mirror twice from opposite directions with a short time delay t_d.
- This imprints a discrete estimate of the mechanical velocity onto the phase of the light $\phi \sim x(t) - x(t + t_d)$ which can then be read out interferometrically, with the noise spectrum below.



$$N(\nu) = \frac{1}{4\kappa(1-L)|G|^2|\chi_c|^2|\chi_m|^2\cos^2(\frac{\nu t_d + \phi_c}{2})} + N_{BM} + 2\kappa\hbar^2|G|^2|\chi_c|^2\left[1 - \frac{L}{2} + \frac{(1-L)}{\nu^2+\kappa^2/4}[\nu\kappa\sin(\nu t_d) + (\nu^2 - \kappa^2/4)\cos(\nu t_d)]\right]$$

Instantaneous Interaction

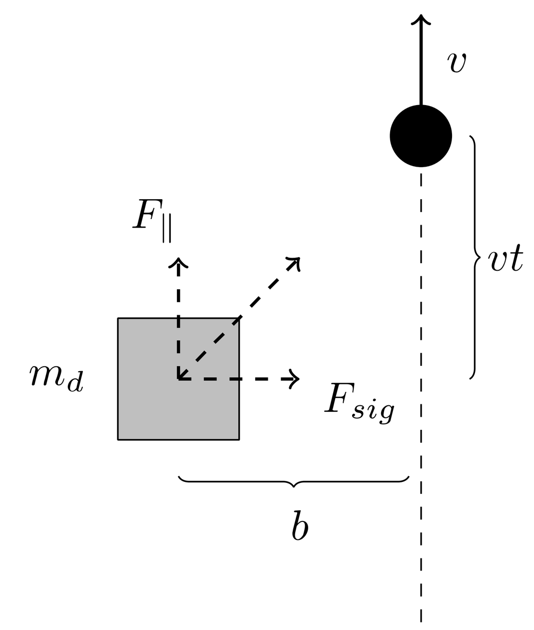
- Consider an instantaneous force signal, $F_{\text{sig}}(t) = \Delta p\,\delta(t - t_0)$

e.g. from collision with background gas particles. We can use this protocol to count individual gas collisions with the sensor. The SNR in this case is

$$\text{SNR}^2 = \frac{\Delta p^2 t_d}{\sqrt{L}\hbar m} \qquad \text{SNR} \approx 1 \times \left(\frac{\Delta p}{10\ \text{keV/c}}\right)\left(\frac{1\ \text{fg}}{m}\right)^{1/2}\left(\frac{10^{-4}}{L}\right)^{1/4}$$

- Compared with the impulse resolution of our position measurement protocol, we do better by a factor of $L^{\frac{1}{4}}$.

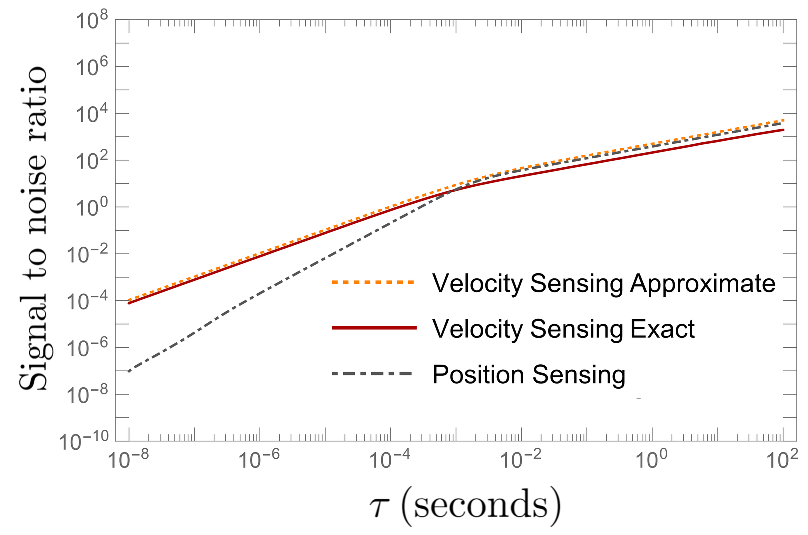
Long-Range Interaction



- We consider a 1/r potential between sensor and incoming particle. The signal is the perpendicular component of the force.

$$F_{\text{sig}} = \frac{\beta b}{(b^2 + v^2t^2)^{3/2}}$$

- For heavy dark matter candidate passing by the sensor at the wind speed of 220 km/s, we obtain an SNR from the gravitational interaction [5].



$$\text{SNR} \approx \frac{G_N m_\chi m_s}{bv\sqrt{\tau N_{BM}}}\frac{1}{\sqrt{(1+\eta)}}$$

$$\approx 10^{-3} \times \left(\frac{m_\chi}{10\ \text{mg}}\right)\left(\frac{m_s}{1\ \text{g}}\right)^{\frac{1}{2}}\left(\frac{\tau}{10\ \text{ns}}\right)\left(\frac{1\ \text{mm}}{b}\right)^2$$

$$\Delta p^2_{\text{noise}} = N_{BM}\tau(1+\eta)$$

- We do better, by a factor of $\eta > 1$, than position measurement.

Conclusion and Future Aims

- Continuous momentum measurement with a pair of ring cavities leads to better sensitivity in measuring small impulses than traditional continuous position measurement.
- This protocol has a wide variety of applications in metrology, particle physics etc. as we have discussed with some examples.
- As a future direction, we can try to improve our velocity measurement protocol with several approaches:
    - time dependent laser drive
    - inductive readout rather than optical