Weak Force Measurement in Bistable Optomechanical System

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ABSTRACT— **One of the main milestones in the study of opto-mechanical system is to increase the sensitivity of weak forces measurement up to the standard quantum limit. We have studied the detection of weak force under a bistable condition in red detuned regime. In this case, dynamics of the system behaves asymptotically similar to stationary state and applying external force affects phase and fluctuation of the cavity field. Using the signal to noise ratio, we have found the sensitivity of the system to external force. The system show the maximum sensitivity in the region where bistability approaches zero. We also studied the destructive effects of thermal noise on the sensitivity. Our approach is based on the covariance matrix formalism which can be solved by first Lyapunov theorem.**

KEYWORDS: Bistable region, cavity opto-mechanics, force measurement, quantum Langevin equation, red detuned regime.

I. INTRODUCTION

Cavity optomechanical systems play an important role in high sensitivity measurement like gravitational-wave detection and atomic force microscope [1, 2]. One way to detect a high sensitivity is to apply a weak force to a moveable mirror in an optical cavity and measure the phase-shift of the reflected beam. The external force exerts a momentum and position shift on the mirror, which in turn induces a phase shift of the reflected optical field in the cavity. Then, one can measure the phase sensitivity of the reflected light that provides the force measurement [3, 4].

The sensitivity in an optical cavity is limited by the thermal noise on the mirror, mechanical degrees of freedom, and unavoidable quantum noise associated with quantum nature of light [5]. The phase noise (shot noise) of the incident light and the radiation pressure noise induce some fluctuations in the position of moveable mirror. Combination of these noises leads to the standard quantum limit for the sensitivity of measurement [6].

Analogous fundamental limitations affect other similar detection devices, such as nano- and micro-electromechanical systems [7]. Fermani *et al.* [1] proposed an optomechanical detection scheme involving a single highly reflecting mirror, shined by an intense highly monochromatic laser pulse. A vibrational mode of the mirror induces two sidebands of the incident field, the Stokes and anti-Stokes sideband. This effect was recently observed in a micro-mechanical resonator as a consequence of the radiation pressure force acting on it. Under appropriate conditions on the duration of the laser pulse, the two sideband modes show significant two mode squeezing, i.e., they are strongly entangled [8].

In fact, Fermani *et al.* [1] considered the limited case of a laser pulse duration much shorter than mechanical relaxation time and neglected all the dynamical effects of damping and thermal noise. Here we drop this assumption and we take into account the effects of the thermal environment acting on the mechanical mode, by adopting a quantum Langevin equation treatment in a single mode optomechanical cavity [8]. Damping and thermal noise have detrimental effects on the force detection sensitivity.

The paper is organized as follows. In Section II we describe the system Hamiltonian and derive the quantum Langevin equations. Then, we derive the linearized equations around the steady state values. In Section III, we discuss the stability conditions in which correlation matrix and bistability parameters are quantified. Using these conditions and parameters, in Section IV we study the force detection sensitivity and finally our conclusion is presented in Section V.

II. THE SYSTEM HAMILTONIAN

The proposed scheme is shown in Fig. 1, a laser beam source, an optical Fabry-Perot cavity in which one of the mirror is much lighter than the other, and a detection system to measure phase variation. In principle, every mechanical resonator has a multitude of normal modes, and every optical resonator likewise has many different modes. The incoming monochromatic laser drive will select one optical cavity resonance frequency.

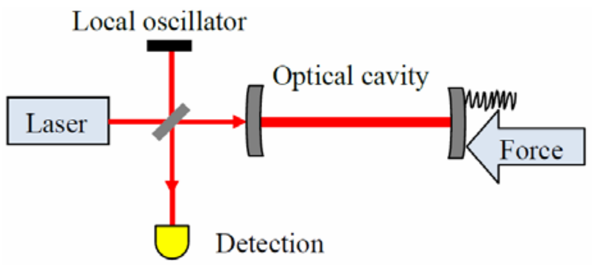

Fig. 1: Schematic description of optomechanical system to detect an external constant force. The cavity mode is driven by the laser at frequency ω_0. External force changes the phase of the cavity field. Using beam splitter, we provide the phase measurement for both input and output fields.

In the case of mechanical motion, all the mechanical resonances will appear in the RF spectrum [9]. However, one can consider a single mechanical mode when a bandpass filter in the detection scheme is used [10]. Then, the motion of the lighter mirror is described by the excitation of one degree of freedom with a single resonant frequencies, ω_m. In the adiabatic limit, the mirror frequency is much smaller than optical cavity resonance frequency $\omega_c = \frac{\pi c}{L}$ (L is the effective length of Fabry-Perot cavity) and mode-mode coupling is negligible. Therefore, we have exclusively considered one optical mode coupled to one mechanical mode.

The cavity is driven at a frequency $\omega_0 = \omega_c - \Delta_0$, in which ω_0 is the driven laser frequency and Δ_0 is cavity detuning. An external constant force exerts on nanomechanical oscillator or moveable mirror that displaces its position. The Hamiltonian of the system is given by

$$H = \hbar\omega_c a^+ a + \frac{\hbar\omega_m}{2}\left(q^2+p^2\right) - \hbar G_o a^+ a q \\ + i\hbar E\left(a^+ e^{-i\omega_0 t} - a e^{i\omega_0 t}\right) + \hbar\omega_m f(t) q \tag{1}$$

where q and p ($[q,p]=i$) are the dimensionless position and momentum operators of the mirror, respectively, a and $a^\dagger$ ($[a,a^\dagger]=1$) are the annihilation and creation operators of the cavity field mode, respectively with frequency ω_c and decay rate κ, and optomechanical coupling $G_0 = \omega_c / L\sqrt{\hbar / m\omega_m}$, where m is the effective mass of the mechanical mode, and L is an effective length of the Fabry-Perot cavity. The first two terms are free harmonic oscillators, and the third term corresponds to optomechanical coupling. The next term describes the input driving by a laser with frequency ω_0, where E is a function of the input laser power as $E = \sqrt{2P\kappa/\hbar\omega_0}$. The last term show that a dimensionless force exerts on the moveable mirror and changes its position (q) which in turn varies the phase of the optical cavity field. Our goal in this paper is to measure this weak force. We take a single mode cavity and neglect the scattering of photons to other cavity modes [8].

The dynamics can be derived by the following set of coupled quantum Langevin equations. In the interaction picture with respect to $\hbar\omega_0 a^\dagger a$

$$\dot{q} = \omega_m p \quad (2)$$

$$\dot{p} = -\omega_m q - \gamma_m p + G_o a^+ a + \omega_m f(t) + \xi(t) \quad (3)$$

$$\dot{a} = -(\kappa + i\Delta_0)a + iG_o aq + E + \sqrt{2\kappa}a_{in} \quad (4)$$

where $\xi(t)$ is the random force exerting on nanomechanical oscillator, γ_m is the damping rate of nanomechanical oscillator. The input noise operator a_{in} associates with the continuum of modes outside the cavity, having the following correlation functions

$$a_{in}(t)a_{in}(t) = a_{in}^\dagger(t)a_{in}(t) = 0 \quad (5)$$

$$a_{in}(t)a_{in}^\dagger(t') = \delta(t-t') \quad (6)$$

Furthermore, $\xi(t)$ is the quantum Langevin force acting on the mirror, with the following function [7]

$$\xi(t)\xi(t') = \frac{\gamma_m}{\omega_m}\int \frac{d\omega}{2\pi} e^{-i\omega(t-t')}\omega\left[\coth\left(\frac{\hbar\omega}{2k_B T}\right)+1\right] \quad (7)$$

Clearly, $\xi(t)$ is not delta-correlated and does not describe a Markovian process. At large mechanical quality factor ($Q_m = \frac{\gamma_m}{\omega_m} \gg 1$) limit, $\xi(t)$ becomes delta-correlated [8],

$$< \xi(t)\xi(t') + \xi(t)\xi(t')/2 > \approx \gamma_m(2n_m+1)\delta(t-t') \quad (8)$$

where $n_m = \left[\exp(\hbar\omega/k_B T) - 1\right]^{-1}$ and it follows a Markovian process (k_B is the Boltzmann constant and T is the mirror temperature). Each Heisenberg operator can be written as c-number steady state plus a fluctuation operator with zero mean value as $a = \alpha_s + \delta a$, $q = q_s + \delta q$ and $p = p_s + \delta p$. Inserting these expressions into the Langevin eqations of Eq. (2) to Eq. (4), they decouple to a set of steady state values and a set of time dependant quantum Langevin equations for the fluctuation operators [8]. The steady state values are given by $p_s = 0$, $q_s = G_0|\alpha_s|^2/\omega_m$, $\alpha_s = E/(\kappa + i\Delta)$, in which α_s is the stationary intracavity field amplitude and the effective cavity detuning (including the radiation pressure effect) is given by $\Delta = \Delta_0 - G_0^2|\alpha_s|^2/\omega_m$. In the case of large amplitude of light, we can neglect the nonlinear terms $\delta a^\dagger \delta a$ and $\delta q \delta a$ and gets the linearized quantum Langevin equations

$$\delta\dot{q} = \omega_m \delta p \quad (9)$$

$$\delta p = -\omega_m \delta q - \gamma_m \delta p + G\delta X + \omega_m f(t) + \xi(t) \quad (10)$$

$$\delta\dot{X} = -\kappa\delta X + \Delta\delta Y + \sqrt{2\kappa}X_{in} \quad (11)$$

$$\delta\dot{Y} = -\kappa\delta Y - \Delta\delta X + G\delta q + \sqrt{2\kappa}Y_{in} \quad (12)$$

If we choose the phase reference then α_s would be real. In order to characterize the time dependent part of the system we define the cavity field quadratures as $\delta X = (\delta a + \delta a^\dagger)/\sqrt{2}$, and $\delta Y = (\delta a - \delta a^\dagger)/i\sqrt{2}$. The correspondent Hermitian noise operators are introduced as $X_{in} = (\delta a_{in} + \delta a_{in}^\dagger)/\sqrt{2}$ and $Y_{in} = (\delta a_{in} - \delta a_{in}^\dagger)/i\sqrt{2}$. The quantum fluctuations of field and oscillator are now coupled by the effective optomechanical coupling $G = \frac{2\omega_c}{L}\Big/\sqrt{\frac{P\kappa}{m\omega_m\omega_0(\kappa^2+\Delta^2)}}$, so that the correlation of the field phase and external force becomes stronger. External force in Eq. (10) affects both position and momentum of the moveable mirror.

III. STABILITY CONDITIONS

In the matrix form, quantum Langevin equations of motion, Eq. (9) to Eq. (12), can be written as

$$\dot{u}(t) = Au(t) + n(t) \tag{13}$$

where $u^T(t) = (\delta q(t), \delta p(t), \delta X(t), \delta Y(t))$, $n^T(t) = (0, \xi(t), \sqrt{2\kappa}X_{in}(t), \sqrt{2\kappa}Y_{in}(t))$ and

$$A = \begin{pmatrix} 0 & \omega_m & 0 & 0 \\ -\omega_m & -\gamma_m & G & 0 \\ 0 & 0 & -\kappa & \Delta \\ G & 0 & \Delta & -\kappa \end{pmatrix} \tag{14}$$

Equation (13) has the solution

$$u(t) = M(t)u(0) + \int_0^t dsM(t-s)n(s) \tag{15}$$

where $M(t) = \exp(At)$. If all the eigenvalues of matrix A have negative values, the system is stable and reaches steady state. The stability condition can be derived by applying the well-known Routh-Hurwitz criterion [11],

$$\begin{aligned} s_1 = 2\gamma_m\kappa\Big\{&\left[\kappa^2 + (\omega_m - \Delta)^2\right]\left[\kappa^2 + (\omega_m + \Delta)^2\right] + \\ &\gamma_m\left[(\gamma_m + 2\kappa)(\kappa^2 + \Delta^2) + 2\kappa\omega_m^2\right]\Big\} + \\ &\Delta\omega_m G^2(\gamma_m + 2\kappa)^2 > 0 \end{aligned} \tag{16}$$

$$s_2 = \omega_m(\kappa^2 + \Delta^2) - G^2\Delta > 0 \tag{17}$$

which will be satisfied hereafter. In the red detuned regime of operation with respect to the cavity ($\Delta > 0$), the first Routh-hurwitz criterion is always satisfied but the second criterion matters. On the other hand, in the blue detuned regime ($\Delta < 0$), the second criterion is always satisfied and just the first one matters.

A. *Correlation Matrix of the System*

Since the dynamics is linearized and noise terms in Eq. (13) are zero-mean quantum Gaussian, the steady state for the system is a two mode Gaussian state that can be characterized by its 4×4 correlation matrix $V_{ij} = \langle u_i(\infty)u_j(\infty) + u_j(\infty)u_i(\infty)\rangle/2$ [12]. Using Eq. (15) in the stable state, we have

$$V_{ij} = \sum_{k,l}\int_0^\infty ds\int_0^\infty ds' M(s)_{ik}\, M(s')_{jl}\, \Phi(s-s')_{kl} \tag{18}$$

where $\Phi(s-s')_{kl} = \langle(\gamma_m + 2\kappa)(\kappa^2 + \Delta^2) + 2\kappa\omega_m^2\rangle/2$ is the matrix of stationary noise correlation functions. Using the noise operators $\xi(t)$ and $a_{in}(t)$, we have $\Phi(s-s')_{kl} = D_{kl}\delta(t-t')$ $\Phi(s-s')_{kl} = D_{kl}\delta(t-t')$, where $D = Diag\left[0, \gamma_m(2n_b+1), \kappa(2n_a+1), \kappa(2n_a+1)\right]$ and correlation matrix becomes:

$$V = \int_0^\infty dsM(s)DM(s)^T \tag{19}$$

which is equivalent to first Lyapunov's theorem [13]

$$\mathrm{AV} + \mathrm{VA}^{\mathrm{T}} = -\mathrm{D} \tag{20}$$

Equation (20) is a linear equation for V and can be straightforwardly solved; but the general exact expression is too cumbersome and will not be reported here.

B. *Bistability*

In the following we restrict our discussion to the red detuned regime where both s_1 and s_2 conditions are fulfilled. We can use Eq. (17) to redefine the dimensionless bistability parameter as

$$\eta = 1 - \frac{G^2\Delta}{\omega_m(\kappa^2 + \Delta^2)} \tag{21}$$

which is a positive number between zero and one. The bistability parameter decreases in the bistable regime and becomes equal to zero at the end of each stable branch [11].

In the bistable regime, the fluctuation around the steady state diverge as one approaches the end of each stable branch and when bistability goes to zero, the system dynamics can suddenly transits to another branch. So in this case, varying the system parameters leads to drastic changes in the system.

We consider an optical cavity with length $L=1$ mm, input power $P_{in}=4\times10^{-4}$ W, and finesse $\mathcal{F}=3.8\times10^{4}$, driven by a laser with $\lambda=810$ nm. The nanomechanical oscillator frequency and damping rate are 10 MHz and 100 Hz and its mass is in the range of 5-30 ng [8,11].

IV. Force Detection Sensitivity

We now consider the real time detection of the constant force f applied to the mirror and determine the sesnsitivity of the optomechanical system by the signal to noise ratio. In this optomechanical devices based on radiation pressure effects, we perform phase sensitive measurement on the reflected beam because the applied force shifts the position of nanonanomechanical oscillator or probe leading to a phase shift of the optical field [14].

In red detuned and bistability regime, as the time passes the system reaches to the steady state. Using Eq. (15), the mean values of the parameter are given as

$$\left\langle u_i\right\rangle = M\left(\infty\right)u_i\left(0\right)+\int_0^{\infty}\left(e^{-At'}\right)_{ij}\left\langle n_j(t')\right\rangle dt' \quad (22)$$

where in steady state, we have $M\left(\infty\right)=0$ and the mean value of the noise term ($<n_i(t)>$) equals zero then we have $<u_i>=0$. But the mean value of squared term or fluctuation is not equal to zero. The fluctuation of the cavity field phase of the measurement is given as follow that is evidently nonzero

$$\begin{aligned}\left\langle Y^2\right\rangle = \int_0^{\infty}\Big\{&\kappa\left[\left(e^{-2At'}\right)_{43}+\left(e^{-2At'}\right)_{44}\right]+\\ &\gamma_m\left(2n_m+1\right)\left(e^{-2At'}\right)_{42}\Big\}dt'\end{aligned} \quad (23)$$

In Eq. (23), the first term corresponds to the fluctuation of amplitude and phase of the optical field and the second term corresponds to Brownian motion of the moveable mirror. On the other hand, the fluctuation is V_{44} in covariance matrix which is calculated in previous section. The mean number of phonons (n_m) and also the fluctuation depends on temperature of nanomechanical bath.

In presence of external force, the mean value of optical phase or signal has a positive value. So the mean value of phase or signal of the system is

$$<Y>=\omega_m\int_0^{\infty}\left(e^{-2At'}\right)_{42}f\left(t'\right)dt' \quad (24)$$

It means that applied force contributes in phase of the system [12]. In order to measure a constant force, the signal must be larger than noise of the system $\left(\dfrac{S}{N}=\dfrac{\left\langle Y\right\rangle}{\sqrt{\left\langle Y^2\right\rangle}}\geq 1\right)$. Then we have

$$SNR=\frac{\omega_m}{\sqrt{\left\langle Y^2\right\rangle}}\int_0^{\infty}f\left(t'\right)\left(e^{-At'}\right)_{42}dt'\geq 1 \quad (25)$$

In the limit of minimum signal that the signal of system equals the fluctuation, we can resort Eq. (25) to find the sensitivity or the minimum measured force as

$$f_{\min}=\frac{\sqrt{\left\langle Y^2\right\rangle}}{\omega_m\int_0^{\infty}\left(e^{-At'}\right)_{42}dt'} \quad (26)$$

The sensitivity depends on T, G, ω_c, κ, ω_m, m, and γ_m. We first consider the behavior of sensitivity versus the mass of nanomechanical oscillator. We have made careful analysis in a wide parameter range and found a parameter region very close to that of performed experimentally and considered theoretically [8].

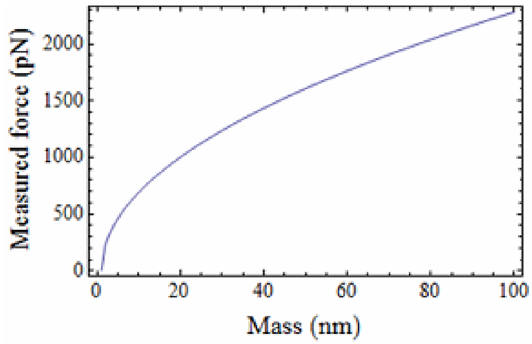

Fig. 2: The sensitivity as a function of the mass of moveable mirror in the red detuned regime. The cavity damping rate, temperature, and effective detuning are $0.4\omega_m$, 0.4K, and $\Delta = \omega_m$.

Figure 2 shows the sensitivity versus the mass of nanomechanical oscillator *m* at temperature 0.4 K. The sensitivity constantly decreases with the increase of mass and temperatures of the system.

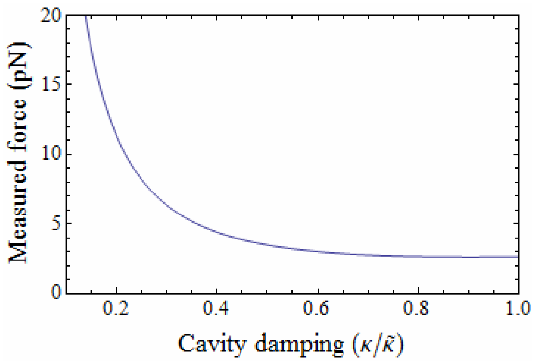

Fig. 3: The sensitivity as a function of the damping rate of optical cavity in the red detuned regime. The mass, temperature and cavity damping scale are 5 nm, 0.4K and $0.4\omega_m$.

Figure 3 shows sensitivity versus the damping rate of optical cavity κ at temperature 0.4 K. In contrast to the above case, the sensitivity increases with increasing the damping rate of optical cavity and approaches zero at large values of κ. The time that optical photons spend in optical cavity is proportional to κ^{-1}. This time also corresponds to distance traveled by photons that both of them increase the sensitivity. Also, in this case the increase of temperature affects the sensitivity.

The sensitivity depends on the effective cavity detuning and temperature of the mechanical bath. The bistability only depends on effective cavity detuning. Figure 4 shows the sensitivity and bistability versus effective cavity detuning at different temperatures 0.4 K, 4 K, and 40 K.

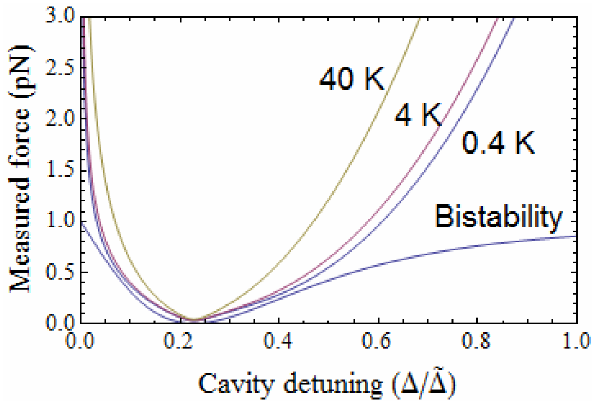

Fig. 4: The sensitivity as a function of effective detuning in the red detuned regime at different temperatures and the bistability parameter is shown which is independent of temperature. The cavity detuning scale and mass are $\tilde{\Delta} = \omega_m$ and 5 nm.

The region in which bistability parameter approaches zero is called bistability region. The minimum measured force or maximum sensitivity coincides with the minimum bistability parameter. As the temperature of the system increases, thermal noise slightly decreases the sensitivity at the bistability region ($\eta \to 0$), but its effects are more noticeable at far regions from bistability. Therefore, in an experimental setup, one should tune the system in bistability and red detuned region in order to measure the highest sensitivity.

In the case of time dependent force, we can apply periodic forces $\left(f(t) = f_0 \sin(\omega_m t)\right)$ on nanomechanical oscillator. Using Eq. (26), the system is able to measure the amplitude of periodic forces which results in similar behavior in case of constant force [15]. When frequency of external force is equal to the frequency of nanomechanical oscillator ($\omega_f = \omega_m$), the maximum sensitivity is obtained that is equal to the case of constant force in Fig. 4.

V. CONCLUSION

We have proposed a red detuned bistable optomechanical system, that is able to measure a constant external force in a linearized regime. The sensitivity decreases when the mass of nanonanomechanical oscillator increases and also it increases when the cavity damping increases. If we consider the effects of both mass and damping rate, the sensitivity at first increases and then decreases and shows the maximum value at the region that bistability parameter approaches zero. When the temperature increases, the destruction effects of thermal noise on the sensitivity are negligible in the region that bistability parameter approaches to zero ($\eta \to 0$). But, when the bistability parameter increases ($\eta \gg 0$), the sensitivity of the system decreases. Therefore, in order to measure an external force, one can tune the system at the state in which bistability parameter approaches to zero.

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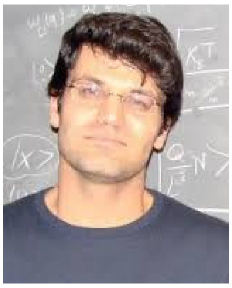

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