

Continuous Measurements and Feedback Control of a Quantum Harmonic Oscillator

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Acronyms

QHO Quantum Harmonic Oscillator. 2

Acknowledgements

Abstract

This is the abstract

Popular Science Summary

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1 Introduction

As our society is becoming increasingly dependent on technology, the demand for better and more efficient technologies is growing. One kind of technology which has been really important since its conception during the second world war by Alan Turing is computers [1]. The field of computer science has been researched a lot during the second half of the 20th century but has hit a fundamental problem. Our current classical computers have reached a limit where the transistors cannot get any smaller without quantum mechanics causing issues [1]. This has prompted research into quantum technologies such as quantum computers and quantum simulations [1].

To properly understand how quantum mechanical systems work, it is important to understand what happens to them when they are interacted with, during for example a measurement [2]. It is also this interaction with a quantum system, which has prompted many interpretations of quantum mechanics and given rise to what is known as the measurement problem [2]. The measurement problem is a fundamental philosophical problem in quantum mechanics, which arises since a quantum mechanical state evolves deterministically according to the Schrödinger equation, but collapses probabilistically when measured or interacted with [2].

It is also interesting to see how such a system can be manipulated to create a certain state which can be used for a specific purpose. This could include, but is not limited to, creating a qubit state to be used in a quantum computer or a state which can simulate a certain physical system [1]. Here it is important to understand the effect feedback has on a measured system, and how to utilize this to create a desired state [3].

This thesis will look at a quantum harmonic oscillator which is coupled to an environment. Thus creating an open quantum system whose state is temperature dependent. The system will be measured continuously using weak measurements with a feedback loop to control the system. The goal is to see how the system evolves under these conditions, and how the feedback loop can be changed and manipulated to observe different behaviours.

1.1 Outline

This text will start in section 2 by introducing the theoretical framework central in this thesis by first defining what we mean by a quantum harmonic oscillator as well as shortly introducing the density matrix formalism of quantum mechanics. Then, we will move on to discuss open

quantum systems and the mathematical framework for the evolution of this type of system, and here we will define a Markovian master equation in Lindblad form. We then move on to discussing measurements on open systems as well as feedback control, and how these concepts can be introduced in the master equation to allow for a mathematical description of the evolution of the system under these effects. In section 3 we will use what has been discussed to derive equations of motion for the QHO. In section 4 there will be a discussion of the relevancy of the results obtained in section 3.

2 Theoretical Framework

2.1 Quantum Harmonic Oscillator

The Quantum Harmonic Oscillator (QHO) is a quantum mechanical system useful for many applications. This stems from the fact that many systems can be approximated as harmonic, that is quadratic, close to their equilibrium position, and since the QHO is a simple system, which is possible to solve analytically it is a good starting approximation. Let us start by assuming that a bosonic particle with mass m is confined in a harmonic potential, then the system has the Hamiltonian

$$\hat{H} = \frac{\hat{p}^2}{2m} + \frac{1}{2}m\omega^2\hat{x}^2 = \hbar\omega \left(\hat{a}^\dagger\hat{a} + \frac{1}{2} \right), \quad (1)$$

where \hat{p} and \hat{x} are the momentum and position operators, m is the mass of the particle, and ω is the angular frequency of the oscillator. The operators \hat{a}^\dagger and \hat{a} are the creation and annihilation operators, collectively referred to as the ladder operators, which are defined as

$$\hat{a} = \sqrt{\frac{m\omega}{2\hbar}} \left(\hat{x} + \frac{i}{m\omega}\hat{p} \right) \quad \text{and} \quad \hat{a}^\dagger = \sqrt{\frac{m\omega}{2\hbar}} \left(\hat{x} - \frac{i}{m\omega}\hat{p} \right). \quad (2)$$

These operators can be used to define the number operator $\hat{n} = \hat{a}^\dagger\hat{a}$ which has the number states, or Fock states, $|n\rangle$ as its eigenstates with eigenvalue n [4]. The ladder operators have a useful the commutation relation $[\hat{a}, \hat{a}^\dagger] = \mathbb{1}$. The Fock states are also eigenstates to the ladder operators with properties

$$\hat{a} |n\rangle = \sqrt{n} |n-1\rangle, \quad (3)$$

$$\hat{a}^\dagger |n\rangle = \sqrt{n+1} |n+1\rangle, \quad (4)$$

which means that they change the excitation level of the QHO [4].

2.2 Open Quantum Systems

Before introducing what open quantum systems we will shortly introduce the language of density matrices. A density matrix describes an ensemble of states defined as

$$\hat{\rho} = \sum_i p_i |\psi_i\rangle \langle \psi_i|, \quad (5)$$

where there is probability p_i for the system to be prepared in the state $|\psi_i\rangle$ [1]. Two conditions imposed on a density matrix is that it I) has unit trace, and II) is positive semi-definite [1]. These conditions ensure that the probabilities are $0 \leq p_i \leq 1$ and $\sum_i p_i = 1$ and that the density matrix is hermitian. With this we can reformulate the postulates of quantum mechanics using density matrices [1].

With an open quantum system we mean a quantum system which in some ways interact with an environment. This interaction could be described as a thermal coupling between the main system and some temperature bath. This will cause the system to be in a thermal equilibrium with the environment if left alone, and therefore it will be dependent on the temperature. Unless the temperature of the bath is zero, the system will be in a mixed state, described by a density matrix $\hat{\rho}$. Notably, if the temperature is zero, the system is purely dissipative since the coupling is thermal. [3]

The thermal coupling to the environment will lead to dissipation of quantum information from the system to the environment. During this process, the system loses coherence. That is, the quantum mechanical properties of the system are lost and a classical description of the state becomes more appropriate. The coherence of the system is manifested in the off-diagonal elements of the density matrix. If the off-diagonal elements are zero, either by dissipation to the environment or by other means of decoherence, the system will exist in a classical probabilistic state, and any superposition of states will be lost. [3]

The combination of the system and environment can be considered a closed system, though more complicated than the main system itself. Then, by performing a partial trace over the environment, a description of the system alone arises at the cost of losing information about the correlation between the two parts [3]. This introduces an uncertainty in the state, and it is therefore necessary to treat the resulting system to be in a mixed state. To describe the

evolution of this system with a master equation two approximations about the coupling need to be performed. Firstly, we need to consider the Born approximation, which says that the coupling between the system and environment is such that only negligible excitations appear in the environment [5]. The other approximation is the Markov approximation saying that the excitations that do appear in the environment will decay much faster than the timescale that the system varies on, and that the system's time evolution is only affected by the current state of the system and not previous states [5]. Together these approximations allow us to write the total density matrix as

$$\rho_{SE} = \rho_S \otimes \rho_E, \quad (6)$$

and derive a Markovian master equation.

2.2.1 Master Equation

The evolution of an open quantum system can be described by a master equation, which is a differential equation and generalization of the Schrödinger equation to involve open quantum systems instead of pure states [3]. By introducing the super operator

$$\mathcal{D}[\hat{L}_k]\hat{\rho} = \hat{L}_k\hat{\rho}\hat{L}_k^\dagger - \frac{1}{2}\left\{\hat{L}_k^\dagger\hat{L}_k, \hat{\rho}\right\}, \quad (7)$$

where \hat{L}_k are called Lindblad operators, the master equation on Lindblad form can be written as

$$\partial_t\hat{\rho} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}] + \sum_k \gamma_k \mathcal{D}[\hat{L}_k]\hat{\rho}, \quad (8)$$

where \hat{H} is the Hamiltonian of the system, and γ_k are the decay rates of the system, relating the decoherence to the environment depending on the coupling to the system [3]. If $\gamma_k = 0$ for all k the equation reduces to the von Neumann equation for a closed quantum system and the coupling to the bath is removed. The remaining term thus describes the unitary time evolution of the system and is the analogue of the Schrödinger equation for the density matrix formalism [3]. At this stage one might also introduce the Liouvillian superoperator and write the master equation more compactly as

$$\partial_t\hat{\rho} = \mathcal{L}\hat{\rho}. \quad (9)$$

This compactness will be useful when considering other types of perturbing effects on the system such as measurements and feedback [3].

In the case considered in this thesis with a QHO coupled to a thermal reservoir we can imagine that we have two types of decay. One decay of particles into the system and one decay of particles out of the system [4]. As mentioned in Sec. 2.1 the ladder operators can be used to excite or deexcite a system. It is also reasonable to assume that the decay, or the amount of particles flowing between the systems and the environment, is proportional to the thermal excitation \bar{n} defined by

$$\bar{n} = \frac{1}{e^{\hbar\omega/k_B T} - 1}, \quad (10)$$

where T is the temperature of the bath and k_B is the Boltzmann constant [4]. If one goes through the mathematical proof one can show that the Lindblad operators can be chosen as $\hat{L}_1 = \hat{a}$ and $\hat{L}_2 = \hat{a}^\dagger$ with coefficients $\gamma_1 = \gamma(\bar{n} + 1)$ and $\gamma_2 = \gamma\bar{n}$, where γ is a decay rate. We can also note that \hat{L}_1 and γ_1 refer to the spontaneous emission from the system to the environment while \hat{L}_2 refer to spontaneous absorption from the environment to the system, consistent with what we know about ladder operators from Sec. 2.1 [4]. Notably, for $T = 0$, the thermal occupation is $\bar{n} = 0$ and the system will only exhibit emission and will decay.

2.3 Continuous Measurements

Measurement is a process which introduces decoherence in the system, and it is therefore interesting to look at its effects [2]. The simplest view on measurements takes the form of von Neumann measurements. This type of measurement is described by a set of measurement operators which projects the system onto the eigenstates of the observable [3]. This essentially means that all quantum information in the system is lost and full decoherence has happened. By generalizing the measurement theory one can derive what is called Positive Operator-Valued Measurement (POVM) [3].

Since the POVM is not necessarily a projective von Neumann measurement all coherence need not be lost after the measurement. Thus, this opens up for the possibility of performing time continuous weak measurement [3]. To describe this type of POVM we first consider a Gaussian measurement operator

$$\hat{K}(z) = \left(\frac{2\bar{\lambda}}{\pi}\right)^{1/4} e^{-\bar{\lambda}(z-\hat{A})^2}, \quad (11)$$

where $\bar{\lambda}$ represents the strength of the measurement, z is a continuous outcome of the measurement, and \hat{A} is the measured observable [3]. We note that the outcome of such a measurement

is described by

$$\langle \hat{A} \rangle = \frac{\hat{K}(z)\hat{\rho}\hat{K}^\dagger(z)}{p(z)}, \quad (12)$$

where the probability is defined as $p(z) = \text{tr}(\hat{K}^\dagger(z)\hat{K}(z)\hat{\rho})$ [3].

Then by discretizing the time interval to segments of dt and defining $\bar{\lambda} = \lambda dt$ we approach a situation where in the limit $dt \rightarrow 0$ all measurements will be weak, and the coherence of the system is minimally affected [3]. Considering the stochastic nature of the process and averaging the possible trajectories one can derive the master equation [3] in Lindblad form to be

$$\partial_t \hat{\rho} = \mathcal{L}\hat{\rho} + \lambda \mathcal{D}[\hat{A}]\hat{\rho}. \quad (13)$$

2.4 Feedback Control

Until this point we have only considered measurements where we omit the information about the measurement outcome. That is, we interact with the system and look at how it evolves due to this interaction on average, instead of looking at the specific outcome of any given measurement [3]. However, now we want to consider feedback control of the system, and thus we will need to include the information about the measurement outcome [3]. Specifically, for a measurement outcome z we will consider a linear feedback modification of \mathcal{L} such that

$$\mathcal{L} \rightarrow \mathcal{L} + z\mathcal{K}, \quad (14)$$

where \mathcal{K} is a superoperator describing the feedback on the system [3] which takes the form

$$\mathcal{K}\hat{\rho} = -\frac{i}{\hbar} [\hat{H}_d, \hat{\rho}], \quad (15)$$

where \hat{H}_d is the Hamiltonian of the driving force on the system. We will consider a driving Hamiltonian which is linear on the form

$$\hat{H}_d = f^* \hat{a} + f \hat{a}^\dagger, \quad (16)$$

where f is the feedback amplitude [6]. Starting from the same place as one derives Eq. (13) we can derive a master equation including feedback [3] to be

$$\partial_t \hat{\rho} = \mathcal{L}\hat{\rho} + \lambda \mathcal{D}[\hat{A}]\hat{\rho} + \frac{1}{2} \mathcal{K} \{ \hat{A}, \hat{\rho} \} + \frac{1}{8\lambda} \mathcal{K}^2 \hat{\rho}, \quad (17)$$

where the square on \mathcal{K} means $\mathcal{K}^2\hat{\rho} = \mathcal{K}(\mathcal{K}\hat{\rho})$.

2.5 Wigner Function

3 Result

Consider a QHO described by the Hamiltonian in Eq. (1) which is coupled to a thermal bath with temperature T . If the oscillator's position quadrature is also continuously measured the evolution of the system can be described by the master equation in Eq. (13) using the Lindblad operators mentioned in Sec. 2.2.1. We want to solve for the equations of motions when measuring for the position quadrature

$$\partial_t \langle \hat{x}^2 \rangle = \text{tr}(\hat{x}^2 \partial_t \hat{\rho}), \quad (18)$$

$$\partial_t \langle \hat{p}^2 \rangle = \text{tr}(\hat{p}^2 \partial_t \hat{\rho}), \quad (19)$$

$$\partial_t \langle \{\hat{x}, \hat{p}\} \rangle = \text{tr}(\{\hat{x}, \hat{p}\} \partial_t \hat{\rho}). \quad (20)$$

The choice of looking at the second momenta has to do with their relation to the variance and thus the fluctuations of the system. These fluctuations are then related to the energy contained in the oscillator. When looking at feedback control and interesting application is to minimize the energy in the oscillator and, which is thus also an argument for looking at the second momenta. Solving Eqs. (18) to (20) yields the following EOM

$$\partial_t \langle \hat{x}^2 \rangle = -\gamma \langle \hat{x}^2 \rangle + \frac{1}{m} \langle \{\hat{x}, \hat{p}\} \rangle + \frac{\gamma \hbar}{m\omega} (\bar{n} + 1/2), \quad (21)$$

$$\partial_t \langle \hat{p}^2 \rangle = -\gamma \langle \hat{p}^2 \rangle - m\omega^2 \langle \{\hat{x}, \hat{p}\} \rangle + \gamma m\omega \hbar (\bar{n} + 1/2) + \lambda \hbar^2, \quad (22)$$

$$\partial_t \langle \{\hat{x}, \hat{p}\} \rangle = -\gamma \langle \{\hat{x}, \hat{p}\} \rangle + 2m\omega^2 \langle \hat{x}^2 \rangle - \frac{2}{m} \langle \hat{p}^2 \rangle \quad (23)$$

for more detailed calculations see App. B. Performing a change of variable to make the equations dimensionless

$$\tilde{x} = \sqrt{\frac{m\omega}{\hbar}} x \quad \text{and} \quad \tilde{p} = \sqrt{\frac{1}{m\omega\hbar}} p, \quad (24)$$

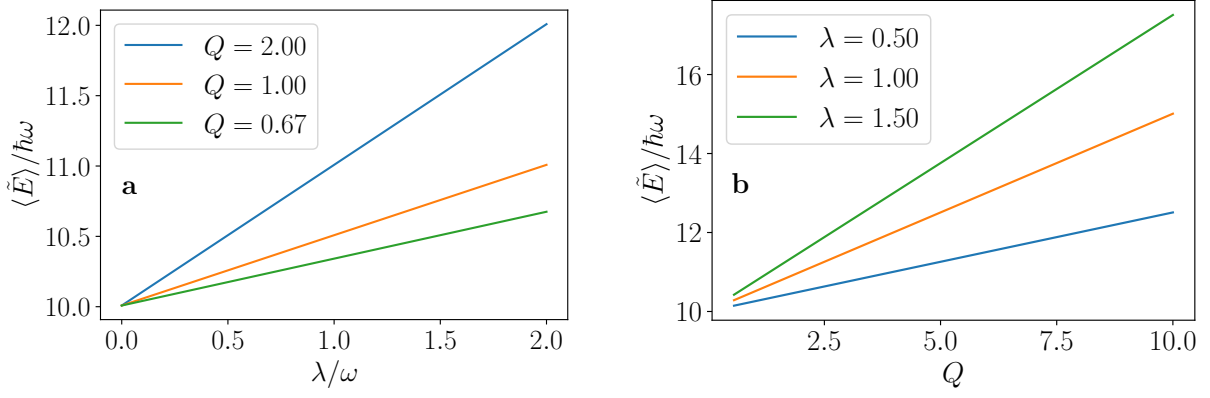


Figure 1: Both figures show the plot in Eq. (27) with the parameters $k_B T = 10$ and $\omega = \hbar = 1$. Figure **a** is plotted against λ/ω and with three different values for Q . All three lines are linear, and the slope increases for increasing Q . Figure **b** is plotted against Q and three different values of λ . All three lines are linear, and the slope increases for increasing λ .

we can solve for the steady state. By introducing the quality factor $Q = \omega/\gamma$ we obtain the steady state solutions

$$\langle \tilde{x}^2 \rangle_{\text{ss}} = (\bar{n} + 1/2) + \frac{\lambda \hbar}{m \omega^2} \frac{2Q^3}{4Q^2 - 1}, \quad (25)$$

$$\langle \tilde{p}^2 \rangle_{\text{ss}} = (\bar{n} + 1/2) + \frac{\lambda \hbar}{m \omega^2} \left(Q - \frac{2Q^3}{4Q^2 - 1} \right), \quad (26)$$

One interesting aspects of the equations is that both equations have identical terms capturing the thermal aspect of the fluctuations. Another interesting thing is that without measurement the equations are only thermal, which is to be expected, however, we get a denominator which diverges for $Q = 1/2$ for both terms. One explanation for this could be that the assumptions and approximations made in the end of Sec. 2.2 about the strength of the coupling makes the master equation invalid for Q of this size. Interestingly, when calculating the energy of the steady state the diverging terms cancel each other, and we get

$$E_{\text{ss}} = \langle \tilde{H} \rangle_{\text{ss}} = \frac{\hbar \omega}{2} (\langle \tilde{p}^2 \rangle + \langle \tilde{x}^2 \rangle) = \hbar \omega (\bar{n} + 1/2) + \frac{\lambda \hbar^2}{2m \omega} Q \quad (27)$$

Looking at Fig. 1 one can see that a stronger measurement correlates to the system steady state increasing in energy, as does it for an increasing quality factor. Both also affect the system linearly. Thus, by continuously measuring the system we add energy into it, which make the steady state higher in energy than what the thermal effects from the bath would otherwise place it. That is, if we do not perform any measurement the system would be stable at around $\bar{n} + 1/2$

which for the parameters used here would give $\langle \tilde{E} \rangle \approx 10\hbar\omega$

4 Discussion

5 Outlook

References

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A Appendix

B EOM Calculation

Consider a quantum harmonic oscillator described by the Hamiltonian

$$\hat{H} = \hbar\omega(\hat{a}^\dagger\hat{a} + 1/2). \quad (28)$$

Consider also that the quantum harmonic oscillator is subject to a temperature bath and is continuously measured. The system then evolves according to the master equation

$$\partial_t \hat{\rho} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}] + \gamma(\bar{n} + 1)\mathcal{D}[\hat{a}]\hat{\rho} + \gamma\bar{n}\mathcal{D}[\hat{a}^\dagger]\hat{\rho} + \lambda\mathcal{D}[\hat{A}]\hat{\rho} \quad (29)$$

where γ is the damping rate, \bar{n} is the thermal occupancy defined as

$$\bar{n} = \frac{1}{e^{\hbar\omega/k_B T} - 1}, \quad (30)$$

λ is the measurement rate, \hat{A} is the measurement operator, and $\mathcal{D}[\hat{O}]$ is the Lindblad super operator defined as

$$\mathcal{D}[\hat{O}]\hat{\rho} = \hat{O}\hat{\rho}\hat{O}^\dagger - \frac{1}{2}\{\hat{O}^\dagger\hat{O}, \hat{\rho}\}. \quad (31)$$

Then we also have the quadrature operators defined as

$$\hat{x} = \sqrt{\frac{\hbar}{2m\omega}}(\hat{a} + \hat{a}^\dagger), \quad \hat{p} = i\sqrt{\frac{m\omega\hbar}{2}}(\hat{a} - \hat{a}^\dagger). \quad (32)$$

We want to find the equations of motion when measuring the position quadrature

$$\partial_t \langle \hat{x}^2 \rangle = \text{tr}(\hat{x}^2 \partial_t \hat{\rho}) \quad (33)$$

$$\partial_t \langle \hat{p}^2 \rangle = \text{tr}(\hat{p}^2 \partial_t \hat{\rho}) \quad (34)$$

$$\partial_t \langle \{\hat{x}, \hat{p}\} \rangle = \text{tr}(\{\hat{x}, \hat{p}\} \partial_t \hat{\rho}). \quad (35)$$

We start by defining the Liouvillian super operator

$$\mathcal{L}\hat{\rho} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}] + \gamma(\bar{n} + 1)\mathcal{D}[\hat{a}]\hat{\rho} + \gamma\bar{n}\mathcal{D}[\hat{a}^\dagger]\hat{\rho} \quad (36)$$

which turns the master equation into

$$\partial_t \hat{\rho} = \mathcal{L} \hat{\rho} + \lambda \mathcal{D}[\hat{x}] \hat{\rho}. \quad (37)$$

B.1 Solving for $\partial_t \langle \hat{x}^2 \rangle$

We can write Eq. (33) as

$$\partial_t \langle \hat{x}^2 \rangle = \text{tr}(\hat{x}^2 \mathcal{L} \hat{\rho}) + \text{tr}(\hat{x}^2 \lambda \mathcal{D}[\hat{x}] \hat{\rho}) \quad (38)$$

and then rewriting the left term using the creation and annihilation operators we get

$$\text{tr}(\hat{x}^2 \mathcal{L} \hat{\rho}) = \frac{\hbar}{2m\omega} \text{tr}\left((\hat{a}^2 + (\hat{a}^\dagger)^2 + \hat{a}\hat{a}^\dagger + \hat{a}^\dagger\hat{a}) \mathcal{L} \hat{\rho}\right) \quad (39)$$

$$= \frac{\hbar}{2m\omega} \left[\text{tr}(\hat{a}^2 \mathcal{L} \hat{\rho}) + \text{tr}((\hat{a}^\dagger)^2 \mathcal{L} \hat{\rho}) + \text{tr}(\hat{a}\hat{a}^\dagger \mathcal{L} \hat{\rho}) + \text{tr}(\hat{a}^\dagger\hat{a} \mathcal{L} \hat{\rho}) \right] \quad (40)$$

Solving these separately

$$\text{tr}(\hat{a}^2 \mathcal{L} \hat{\rho}) = -\frac{i}{\hbar} \text{tr}\left(\hat{a}^2 [\hat{H}, \hat{\rho}]\right) + \gamma(\bar{n} + 1) \text{tr}(\hat{a}^2 \mathcal{D}[\hat{a}] \hat{\rho}) + \gamma\bar{n} \text{tr}(\hat{a}^2 \mathcal{D}[\hat{a}^\dagger] \hat{\rho}) \quad (41)$$

$$= -i\omega \text{tr}(\hat{a}^2 \hat{a}^\dagger \hat{a} \hat{\rho}) + i\omega \text{tr}(\hat{a}^2 \hat{\rho} \hat{a}^\dagger \hat{a}) \quad (42)$$

$$+ \gamma(\bar{n} + 1) \text{tr}(\hat{a}^3 \hat{\rho} \hat{a}^\dagger) - \frac{\gamma(\bar{n} + 1)}{2} \text{tr}(\hat{a}^2 \hat{a}^\dagger \hat{a} \hat{\rho}) - \frac{\gamma(\bar{n} + 1)}{2} \text{tr}(\hat{a}^2 \hat{\rho} \hat{a}^\dagger \hat{a}) \quad (43)$$

$$+ \gamma\bar{n} \text{tr}(\hat{a}^2 \hat{a}^\dagger \hat{\rho} \hat{a}) - \frac{\gamma\bar{n}}{2} \text{tr}(\hat{a}^3 \hat{a}^\dagger \hat{\rho}) - \frac{\gamma\bar{n}}{2} \text{tr}(\hat{a}^2 \hat{\rho} \hat{a} \hat{a}^\dagger) \quad (44)$$

Using cyclic permutations of the trace and combining terms we get

$$\text{tr}(\hat{a}^2 \mathcal{L} \hat{\rho}) = i\omega \text{tr}\left([\hat{a}^\dagger \hat{a}, \hat{a}^2] \hat{\rho}\right) + \frac{\gamma(\bar{n} + 1)}{2} \text{tr}\left([\hat{a}^\dagger \hat{a}, \hat{a}^2] \hat{\rho}\right) + \frac{\gamma\bar{n}}{2} \text{tr}\left([\hat{a}^2, \hat{a} \hat{a}^\dagger] \hat{\rho}\right) \quad (45)$$

The commutators are

$$[\hat{a}^\dagger \hat{a}, \hat{a}^2] = [\hat{a}^\dagger, \hat{a}^2] \hat{a} = \hat{a} [\hat{a}^\dagger, \hat{a}] \hat{a} + [\hat{a}^\dagger, \hat{a}] \hat{a}^2 = -2\hat{a}^2 \quad (46)$$

$$[\hat{a}^2, \hat{a} \hat{a}^\dagger] = \hat{a} [\hat{a}^2, \hat{a}^\dagger] = \hat{a}^2 [\hat{a}, \hat{a}^\dagger] + \hat{a} [\hat{a}, \hat{a}^\dagger] \hat{a} = 2\hat{a}^2 \quad (47)$$

Thus

$$\text{tr}(\hat{a}^2 \mathcal{L} \hat{\rho}) = -2i\omega \text{tr}(\hat{a}^2 \hat{\rho}) - \gamma(\bar{n} + 1) \text{tr}(\hat{a}^2 \hat{\rho}) + \gamma\bar{n} \text{tr}(\hat{a}^2 \hat{\rho}) = -(\gamma + 2i\omega) \text{tr}(\hat{a}^2 \hat{\rho}) \quad (48)$$

$$= -(\gamma + 2i\omega) \langle \hat{a}^2 \rangle. \quad (49)$$

By taking the hermition conjugate of the above we get

$$\text{tr}\left((\hat{a}^\dagger)^2 \mathcal{L}\hat{\rho}\right) = (\gamma - 2i\omega) \text{tr}\left((\hat{a}^\dagger)^2 \hat{\rho}\right) = -(\gamma - 2i\omega) \left\langle (\hat{a}^\dagger)^2 \right\rangle. \quad (50)$$

Now we do the same for $\text{tr}(\hat{a}^\dagger \hat{a} \mathcal{L}\hat{\rho})$, so

$$\text{tr}(\hat{a}^\dagger \hat{a} \mathcal{L}\hat{\rho}) = -\frac{i}{\hbar} \text{tr}\left(\hat{a}^\dagger \hat{a} [\hat{H}, \hat{\rho}]\right) + \gamma(\bar{n} + 1) \text{tr}\left(\hat{a}^\dagger \hat{a} \mathcal{D}[\hat{a}]\hat{\rho}\right) + \gamma\bar{n} \text{tr}\left(\hat{a}^\dagger \hat{a} \mathcal{D}[\hat{a}^\dagger]\hat{\rho}\right) \quad (51)$$

$$= -i\omega \text{tr}\left(\hat{a}^\dagger \hat{a} \hat{a}^\dagger \hat{a} \hat{\rho}\right) + i\omega \text{tr}\left(\hat{a}^\dagger \hat{a} \hat{\rho} \hat{a}^\dagger \hat{a}\right) \quad (52)$$

$$+ \gamma(\bar{n} + 1) \text{tr}\left(\hat{a}^\dagger \hat{a}^2 \hat{\rho} \hat{a}^\dagger\right) - \frac{\gamma(\bar{n} + 1)}{2} \text{tr}\left(\hat{a}^\dagger \hat{a} \hat{a}^\dagger \hat{a} \hat{\rho}\right) - \frac{\gamma(\bar{n} + 1)}{2} \text{tr}\left(\hat{a}^\dagger \hat{a} \hat{\rho} \hat{a}^\dagger \hat{a}\right) \quad (53)$$

$$+ \gamma\bar{n} \text{tr}\left(\hat{a}^\dagger \hat{a} \hat{a}^\dagger \hat{\rho} \hat{a}\right) - \frac{\gamma\bar{n}}{2} \text{tr}\left(\hat{a}^\dagger \hat{a}^2 \hat{a}^\dagger \hat{\rho}\right) - \frac{\gamma\bar{n}}{2} \text{tr}\left(\hat{a}^\dagger \hat{a} \hat{\rho} \hat{a} \hat{a}^\dagger\right) \quad (54)$$

using cyclic permutations of the trace and combining terms we get

$$\text{tr}(\hat{a}^\dagger \hat{a} \mathcal{L}\hat{\rho}) = i\omega \text{tr}\left([\hat{a}^\dagger \hat{a}, \hat{a}^\dagger \hat{a}]\hat{\rho}\right) + \gamma(\bar{n} + 1) \text{tr}\left((\hat{a}^\dagger)^2 \hat{a}^2 \hat{\rho}\right) - \gamma(\bar{n} + 1) \text{tr}\left(\hat{a}^\dagger \hat{a} \hat{a}^\dagger \hat{a} \hat{\rho}\right) \quad (55)$$

$$+ \gamma\bar{n} \text{tr}\left(\hat{a} \hat{a}^\dagger \hat{a} \hat{a}^\dagger \hat{\rho}\right) - \frac{\gamma\bar{n}}{2} \text{tr}\left(\hat{a}^\dagger \hat{a}^2 \hat{a}^\dagger \hat{\rho}\right) - \frac{\gamma\bar{n}}{2} \text{tr}\left(\hat{a} (\hat{a}^\dagger)^2 \hat{a} \hat{\rho}\right) \quad (56)$$

Commuting to simplify we get

$$\text{tr}(\hat{a}^\dagger \hat{a} \mathcal{L}\hat{\rho}) = -\gamma(\bar{n} + 1) \text{tr}\left(\hat{a}^\dagger \hat{a} \hat{\rho}\right) - \gamma\bar{n} \text{tr}\left([\hat{a} \hat{a}^\dagger, \hat{a}^\dagger \hat{a}]\hat{\rho}\right) + \gamma\bar{n} \text{tr}\left(\hat{a} \hat{a}^\dagger \hat{\rho}\right) \quad (57)$$

The commutator is equal to 0, and thus we get

$$\text{tr}(\hat{a}^\dagger \hat{a} \mathcal{L}\hat{\rho}) = -\gamma(\bar{n} + 1) \text{tr}\left(\hat{a}^\dagger \hat{a} \hat{\rho}\right) + \gamma\bar{n} + \gamma\bar{n} \text{tr}\left(\hat{a}^\dagger \hat{a} \hat{\rho}\right) = -\gamma \text{tr}\left(\hat{a}^\dagger \hat{a} \hat{\rho}\right) + \gamma\bar{n} = -\gamma \left\langle \hat{a}^\dagger \hat{a} \right\rangle + \gamma\bar{n}. \quad (58)$$

Similarly we can find that

$$\text{tr}(\hat{a} \hat{a}^\dagger \mathcal{L}\hat{\rho}) = -\gamma \text{tr}\left(\hat{a} \hat{a}^\dagger \hat{\rho}\right) + \gamma(\bar{n} + 1) = -\gamma \left\langle \hat{a} \hat{a}^\dagger \right\rangle + \gamma(\bar{n} + 1). \quad (59)$$

Then since \hat{x}^2 commutes with \hat{x} (the measurement operator) we can write Eq. (38) the equation

of motion

$$\partial_t \langle \hat{x}^2 \rangle = \text{tr}(\hat{x}^2 \mathcal{L} \hat{\rho}) \quad (60)$$

$$= \frac{\hbar}{2m\omega} \left(-(\gamma + 2i\omega) \langle \hat{a}^2 \rangle - (\gamma - 2i\omega) \langle (\hat{a}^\dagger)^2 \rangle - \gamma \langle \hat{a}^\dagger \hat{a} \rangle + \gamma \bar{n} - \gamma \langle \hat{a} \hat{a}^\dagger \rangle + \gamma(\bar{n} + 1) \right) \quad (61)$$

$$= -\gamma \frac{\hbar}{2m\omega} \left(\langle \hat{a}^2 \rangle + \langle (\hat{a}^\dagger)^2 \rangle + \langle \hat{a}^\dagger \hat{a} \rangle + \langle \hat{a} \hat{a}^\dagger \rangle \right) + \frac{i\hbar}{m} \left(\langle (\hat{a}^\dagger)^2 \rangle - \langle \hat{a}^2 \rangle \right) + \frac{\gamma\hbar}{m\omega} (\bar{n} + 1/2) \quad (62)$$

Since we have

$$\{\hat{x}, \hat{p}\} = i\hbar((\hat{a}^\dagger)^2 - \hat{a}^2) \quad (63)$$

We can write the equation of motion as

$$\partial_t \langle \hat{x}^2 \rangle = -\gamma \langle \hat{x}^2 \rangle + \frac{1}{m} \langle \{\hat{x}, \hat{p}\} \rangle + \frac{\gamma\hbar}{m\omega} (\bar{n} + 1/2) \quad (64)$$

B.2 Solving for $\partial_t \langle \hat{p}^2 \rangle$

Writing Eq. (34) as

$$\partial_t \langle \hat{p}^2 \rangle = \text{tr}(\hat{p}^2 \mathcal{L} \hat{\rho}) + \text{tr}(\hat{p}^2 \lambda \mathcal{D}[\hat{x}] \hat{\rho}) \quad (65)$$

Rewriting the left terms using \hat{a}, \hat{a}^\dagger we get

$$\text{tr}(\hat{p}^2 \mathcal{L} \hat{\rho}) = -\frac{m\omega\hbar}{2} \text{tr} \left((\hat{a}^2 + (\hat{a}^\dagger)^2 - \hat{a}^\dagger \hat{a} - \hat{a} \hat{a}^\dagger) \mathcal{L} \hat{\rho} \right) \quad (66)$$

$$= -\frac{m\omega\hbar}{2} \left(\text{tr}(\hat{a}^2 \mathcal{L} \hat{\rho}) + \text{tr}((\hat{a}^\dagger)^2 \mathcal{L} \hat{\rho}) - \text{tr}(\hat{a}^\dagger \hat{a} \mathcal{L} \hat{\rho}) - \text{tr}(\hat{a} \hat{a}^\dagger \mathcal{L} \hat{\rho}) \right) \quad (67)$$

We have solved for these before, so we can write

$$\text{tr}(\hat{p}^2 \mathcal{L} \hat{\rho}) = -\frac{m\omega\hbar}{2} \left(-(\gamma + 2i\omega) \langle \hat{a}^2 \rangle - (\gamma - 2i\omega) \langle (\hat{a}^\dagger)^2 \rangle + \gamma \langle \hat{a}^\dagger \hat{a} \rangle - \gamma \bar{n} + \gamma \langle \hat{a} \hat{a}^\dagger \rangle - \gamma(\bar{n} + 1) \right) \quad (68)$$

$$= -\gamma \langle \hat{p}^2 \rangle + mi\omega^2 \hbar \left(\langle \hat{a}^2 \rangle - \langle (\hat{a}^\dagger)^2 \rangle \right) + \gamma m\omega \hbar (\bar{n} + 1/2) \quad (69)$$

$$= -\gamma \langle \hat{p}^2 \rangle - m\omega^2 \langle \{\hat{x}, \hat{p}\} \rangle + \gamma m\omega \hbar (\bar{n} + 1/2) \quad (70)$$

Solving the measurement term

$$\text{tr}(\hat{p}^2 \lambda \mathcal{D}[\hat{x}] \hat{\rho}) = \lambda \left(\text{tr}(\hat{p}^2 \hat{x} \hat{\rho}) - \frac{1}{2} \text{tr}(\hat{p}^2 \hat{x}^2 \hat{\rho}) - \frac{1}{2} \text{tr}(\hat{p}^2 \hat{\rho} \hat{x}^2) \right) \quad (71)$$

$$= \lambda \left(\text{tr}(\hat{x} \hat{p}^2 \hat{x} \hat{\rho}) - \frac{1}{2} \text{tr}(\hat{p}^2 \hat{x}^2 \hat{\rho}) - \frac{1}{2} \text{tr}(\hat{x}^2 \hat{p}^2 \hat{\rho}) \right) \quad (72)$$

Commuting the operators

$$\hat{x} \hat{p}^2 \hat{x} = \frac{1}{2} (\hat{p} \hat{x} + i\hbar) \hat{p} \hat{x} + \frac{1}{2} \hat{x} \hat{p} (\hat{x} \hat{p} - i\hbar) = \frac{1}{2} \hat{p} \hat{x} \hat{p} \hat{x} + \frac{1}{2} \hat{x} \hat{p} \hat{x} \hat{p} + \frac{i\hbar}{2} [\hat{p}, \hat{x}] \quad (73)$$

$$= \frac{1}{2} \hat{p} \hat{x} \hat{p} \hat{x} + \frac{1}{2} \hat{x} \hat{p} \hat{x} \hat{p} + \frac{\hbar^2}{2} \quad (74)$$

$$\hat{p}^2 \hat{x}^2 = \hat{p} (\hat{x} \hat{p} - i\hbar) \hat{x} = \hat{p} \hat{x} \hat{p} \hat{x} - i\hbar \hat{p} \hat{x} \quad (75)$$

$$\hat{x}^2 \hat{p}^2 = \hat{x} (\hat{p} \hat{x} + i\hbar) \hat{p} = \hat{x} \hat{p} \hat{x} \hat{p} + i\hbar \hat{x} \hat{p} \quad (76)$$

This gives

$$\text{tr}(\hat{p}^2 \lambda \mathcal{D}[\hat{x}] \hat{\rho}) = \lambda \left(\frac{1}{2} \text{tr}(\hat{p} \hat{x} \hat{p} \hat{x} \hat{\rho}) + \frac{1}{2} \text{tr}(\hat{x} \hat{p} \hat{x} \hat{p} \hat{\rho}) + \frac{\hbar^2}{2} - \frac{1}{2} \text{tr}(\hat{p} \hat{x} \hat{p} \hat{x} \hat{\rho}) - \frac{1}{2} \text{tr}(\hat{x} \hat{p} \hat{x} \hat{p} \hat{\rho}) + \frac{i\hbar}{2} \text{tr}([\hat{p}, \hat{x}]) \right) \quad (77)$$

$$= \frac{\lambda \hbar^2}{2} + \frac{\lambda i\hbar}{2} \text{tr}([\hat{p}, \hat{x}]) = \lambda \hbar^2 \quad (78)$$

The final equation of motion then becomes

$$\partial_t \langle \hat{p}^2 \rangle = -\gamma \langle \hat{p}^2 \rangle - m\omega^2 \langle \{\hat{x}, \hat{p}\} \rangle + \gamma m\omega \hbar (\bar{n} + 1/2) + \lambda \hbar^2 \quad (79)$$

B.3 Solving for $\partial_t \langle \{\hat{x}, \hat{p}\} \rangle$

Writing Eq. (35) as

$$\partial_t \langle \{\hat{x}, \hat{p}\} \rangle = \text{tr}(\{\hat{x}, \hat{p}\} \mathcal{L} \hat{\rho}) + \text{tr}(\{\hat{x}, \hat{p}\} \lambda \mathcal{D}[\hat{x}] \hat{\rho}) \quad (80)$$

Rewriting the left term as

$$\text{tr}(\{\hat{x}, \hat{p}\} \mathcal{L} \hat{\rho}) = i\hbar \text{tr}((\hat{a}^2 - (\hat{a}^\dagger)^2) \mathcal{L} \hat{\rho}) = i\hbar \text{tr}(\hat{a}^2 \mathcal{L} \hat{\rho}) - i\hbar \text{tr}((\hat{a}^\dagger)^2 \mathcal{L} \hat{\rho}) \quad (81)$$

We have calculated these terms before, so we can write

$$\text{tr}(\{\hat{x}, \hat{p}\} \mathcal{L} \hat{\rho}) = -i\hbar \left((\gamma + 2i\omega) \langle \hat{a}^2 \rangle - (\gamma - 2i\omega) \langle (\hat{a}^\dagger)^2 \rangle \right) \quad (82)$$

$$= -\gamma i\hbar \left(\langle \hat{a}^2 \rangle - \langle (\hat{a}^\dagger)^2 \rangle \right) + 2\hbar\omega \left(\langle \hat{a}^2 \rangle + \langle (\hat{a}^\dagger)^2 \rangle \right) \quad (83)$$

We also have that

$$\hat{a}^2 + (\hat{a}^\dagger)^2 = \frac{m\omega}{\hbar} \hat{x}^2 - \frac{1}{m\omega\hbar} \hat{p}^2 \quad (84)$$

Thus we get

$$\text{tr}(\{\hat{x}, \hat{p}\} \mathcal{L} \hat{\rho}) = -\gamma \langle \{\hat{x}, \hat{p}\} \rangle + 2m\omega^2 \langle \hat{x}^2 \rangle - \frac{2}{m} \langle \hat{p}^2 \rangle \quad (85)$$

Solving for the measurement term

$$\lambda \text{tr}(\{\hat{x}, \hat{p}\} \mathcal{D}[\hat{x}] \hat{\rho}) = \frac{\lambda}{2} \left(\text{tr}([\hat{x}^2, \hat{p}\hat{x}] \hat{\rho}) + \text{tr}([\hat{x}\hat{p}, \hat{x}^2]) \right) \quad (86)$$

Solving the commutators shows that this will become zero.

B.4 Results

The final equations of motion are

$$\partial_t \langle \hat{x}^2 \rangle = -\gamma \langle \hat{x}^2 \rangle + \frac{1}{m} \langle \{\hat{x}, \hat{p}\} \rangle + \frac{\gamma\hbar}{m\omega} (\bar{n} + 1/2) \quad (87)$$

$$\partial_t \langle \hat{p}^2 \rangle = -\gamma \langle \hat{p}^2 \rangle - m\omega^2 \langle \{\hat{x}, \hat{p}\} \rangle + \gamma m\omega\hbar (\bar{n} + 1/2) + \lambda\hbar^2 \quad (88)$$

$$\partial_t \langle \{\hat{x}, \hat{p}\} \rangle = -\gamma \langle \{\hat{x}, \hat{p}\} \rangle + 2m\omega^2 \langle \hat{x}^2 \rangle - \frac{2}{m} \langle \hat{p}^2 \rangle \quad (89)$$