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This is what I was thinking. So like I said before I recognize your P_eq as the equilibrium probability distribution for an oscillator potential. The issue I have is that that probability distribution does not seem to take account for the Brownian Motion. Simply the Brownian motion of the particle obeys the Fokker-Planck equation as you have listed when the external force is zero. Brownian motion yields a time-dependent probability distribution itself. As time increases the particle is more and more likely to be found farther away from the starting point. It is always most likely to be found near the starting point.

This distribution however does not account for the oscillator potential. Just as the oscillator distribution does not account for the Brownian motion. So starting with your Fokker-Planck equation this is the PDE I got to last night that I briefly tried to think of a solution for.

$$\frac{\partial P(x,t)}{\partial t} = D\frac{\partial^2 P(x,t)}{\partial x^2} + \Gamma(P(x,t) - (x - x_0)\frac{\partial P(x,t)}{\partial x}) \tag{1}$$

In the above equation there is what would be the standard diffusion distribution, but its coupled to the forcing. The solution to this equation is not at all apparent to me and perhaps the only way it can be solved is numerically.

To answer your questions. The way that you solved it in your first approach is mathematically correct. However you only found the average potential energy of a particle in an oscillator potential. Furthermore this could be the right answer but right now I do not see why the P(x,t) (the as of yet unknown distribution function) should go to a harmonic oscillator distribution for large t, unless the oscillator potential is overly dominant in this system.

As far your second approach goes I am having trouble following what you are doing and exactly what your assumptions are. So if you could clarify or rephrase for me that would be great.

To a good approximation I think that the harmonic oscillator result that you got is correct. But there is definitely a more detailed solution to the problem.

What is this for is this for research? Or a class?