Lab 5: Magneto-Gravitational Trapping of Diamagnetic Particles

November 16, 2021

1 Introduction

1.1 Background Reading

1. M. Lindner, G. Nir, A. Vivante, and Y. Garini, "Dynamic analysis of a diffusing particle in a trapping potential", Phys. Rev. E 87, 022716 (2013).

2. B. R. Slezak, C. W. Lewandowski, J.-F. Hsu, B. D'Urso, "Cooling the Motion of a Silica Microsphere in a Magneto-Gravitational Trap in Ultra-High Vacuum", New Journal of Physics 20 (6), 063028 (2018), `https://iopscience.iop.org/article/10.1088/1367-2630/aacac1/meta`.

3. M.D. Simon and A. K. Geim, "Diamagnetic levitation: Flying frogs and floating magnets (invited)", J. App. Phys. 87, 6200-6204 (2000).

1.2 Motivation

The purpose of this lab is for you to learn basic vacuum techniques and to explore a simple harmonic oscillator system, a micrometer-scale particle in a magneto-gravitational trap. This system is remarkable for its high quality factor (Q), simplicity, and stability in vacuum.

Levitated optomechanical systems, and particularly particles trapped in vacuum, provide unique platforms for studying the mechanical behavior of objects well-isolated from their environment. Ultimately, such systems may enable the study of fundamental questions in quantum mechanics, gravity, and other weak forces.

1.3 Techniques

In this lab, data will be acquired by analyzing images of the particle taken with a high-speed camera. You will use a pre-written C++ program to acquire images from a Basler acA1920-40um high-speed camera with a Mitutoyo 3X compact objective. The images can be analyzed with trackpy or an algorithm of your own to track the center of the particle from frame to frame.

2 Objectives

These objectives are intended to guide your experiments. They are not a step-by-step procedure.

1. Calibration:
   Measure the camera and objective lens calibration in both horizontal and vertical directions by taking images of the calibration target in two orientations. You should use this calibration for all remaining parts of this lab (convert all data from pixels to meters or μm). Compare your results to the expected calibration based on the specified pixel size of the camera and magnification of the microscope objective.

2. Brownian Motion:

    (a) Make histograms of the displacement of the particle due to thermal motion and the joint probability distribution $P(x_i(t), x_i(t+\Delta t))$ for both the vertical and axial motion at atmospheric pressure.
    CHECKPOINT: Show the instructor or TA your particle trajectory, displacement histogram, and joint probability distribution.

    (b) Repeat the histogram and joint probability distribution measurements at (at least) two lower pressures (e.g. rough and high vacuum). For each joint probability distribution, be sure to choose Δt to be long enough that the distribution is more than one pixel wide but not so long that the distribution becomes circular.

    (c) Plot the thermally-driven motion of the particle at several pressures from atmospheric pressure to high vacuum in the Fourier domain.
    CHECKPOINT: Show the instructor or TA at least one particle motion power spectrum with calibrated x and y axes.

3. Damped Driven Harmonic Oscillator (if time permits):

    (a) Measure the transient response of the particle after "tapping" the table or vacuum chamber at one or more pressures. You may want to save this until last due to a risk of knocking out the particle.

3 Questions

These questions should be specifically answered in your lab notebook, and can also serve as a guide for discussion in your lab report analysis.

1. Using the oscillation frequencies measured under vacuum and the Brownian motion at or near atmospheric pressure, determine the mass of the particle from each of distributions. Assume that the temperature associated with the Brownian motion is 298 K. Why shouldn't you use the Brownian motion at high vacuum?

2. Compare the thermally-driven, coherently-driven, and transient responses in the Fourier domain at all pressures (where data quality is adequate). In each case, carefully fit the particle motion to a driven damped harmonic oscillator model (in the Fourier domain), and compare the results.

3. From your Fourier domain analysis, plot the dependence of the the quality factor (Q) of the particle motion on pressure.

4. **(undergraduates)** Based on your experimental joint probability distributions, what qualitative statements can you make about the dependence of the particle diffusion coefficient on pressure? Why?
    (graduate students) Determine the diffusion coefficient of a particle at several pressures using the joint probability distribution for both the vertical and axial motion. Assume that the temperature associated with the Brownian motion is 298 K.

4 Hints

1. *Loading Technique:* Load particles by dipping a wire into the silicon carbide (SiC) particles and tapping it on the trap. The particles can only enter from the left or right upper side of the trap (from the point of view of the camera), so you want the particle to fall off the wire and drift down and into the trap. It can take tens of seconds for the particle to drift into the trap, so be patient.

2. *Alternate Loading Technique:* There are so many of these particles in the chamber, that just blowing air into the chamber (with the bulb blower) may kick up enough particles for one to drift into the trap. Again, be patient.

3. *Ejecting a Particle:* Use the blower to knock unwanted particles out of the trap.

4. *Cleaning the Trap:* If there is too much debris on the pole pieces, there may be excessive light scattered near the particle, or the particle may even stick to the debris. The pole pieces can be cleaned with vigorous blowing from the bulb.

5. *Illumination:* You can try out different illumination directions, but I have found the best to be illuminating the particle from behind, with the laser aimed at an angle such that the direct beam does not enter the camera microscope objective (it would be too bright if it went straight in). To decrease scattering off the bottom pole piece (which is usually close to the particle), you can also aim the laser slightly up. Keep the intensity down to avoid having the scattering off the pole pieces overwhelm the camera.

6. *Frame Rate:* Particle oscillation frequencies can reach 100 Hz in this trap, so your frame rate should be at least 200 Hz. You will need to record only a very small frame size to get the frame rate up. You also need to choose a small enough frame to cut out scattering off the pole pieces.

7. *Data:* Take a long run of data! You will spend a while setting up, so take perhaps a minute or more of data to get good statistics.