

Physics 262

Lab #2: Optical Tweezers

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## Abstract

This lab served as an introduction to the operation of optical tweezers and to their use in measuring the properties of fluids. Specifically, the storage and loss moduli of a gelatin solution were determined after calibrating the tweezers in water. The spring constant of the trap is determined to be 0.0141 N/m, and the moduli are recorded in a graph in the procedure section of this report.

## Introduction

The basic purpose of this experiment was to use two laser beams to interact with and observe the behavior of 1.5  $\mu\text{m}$  polystyrene beads in liquid solution. One of the lasers was used to capture the bead and cause it to oscillate back and forth at a controlled frequency. The second laser measured the bead's position. In this way, the amplitude of oscillation and the phase difference between application of force and movement of the bead could be determined for various frequencies. These parameters (along with the diameter of the bead) sufficiently characterize the viscoelastic properties of the fluid.

## Theoretical Background

The purpose of optical tweezers is to provide a mechanism for precise manipulation of micron sized particles. This manipulation is achieved by using a laser beam to create a potential well effective upon certain dielectric materials. Typically small dielectric beads are brought into this trap, and through these beads interactions are made with the surrounding environment.

One way to understand the reason the bead is trapped is through the principle of refracted light. The trapping laser, before its incidence upon the dielectric bead, is sent through a lens of wide numerical aperture. Thus, separate 'rays' of the laser (or photons if you will) hit the sides of the spherical bead and are refracted inwards at a different angle. When they have reached another surface of the bead, they are again refracted to yet another angle as they exit. Thus each of the two photons enter at one angle and exit at another. And the change in momentum required to adjust their angle is in turn transferred to the bead.

The key to trapping is that the crossed beams are set up in such a way that the net momentum transferred to the bead is always pointed in the direction of a central focus point. This causes the bead to stay in place rather than succumbing to random Brownian motion, or, if the beam is moved, it causes the bead to follow.

One of the great applications of optical tweezers is in the area of bio-physics. If dielectric beads can be made to adhere to a biological sample, then the laser trap can be used to manipulate said sample. A simple example of this technique is explored in the following experiment, where a gelatin solution is probed via induced vibrations of the dielectric bead.

## Experimental Procedure

### Apparatus

1064 nm trapping laser, telescope (for widening beam), neutral density filter, movable piezo-electric mirror with control box, polarizing cube (for combining two laser beams), 960 nm position sensing laser, microscope, position sensor, oscilloscope, lock-in, labview program

### Procedure

The mechanical setup of the apparatus was configured prior to the start of the lab. The trapping and monitoring laser beams were combined and sent through the sample mount of the microscope. The microscope camera was aimed so as to provide a clear view of the region where the trap was focused.

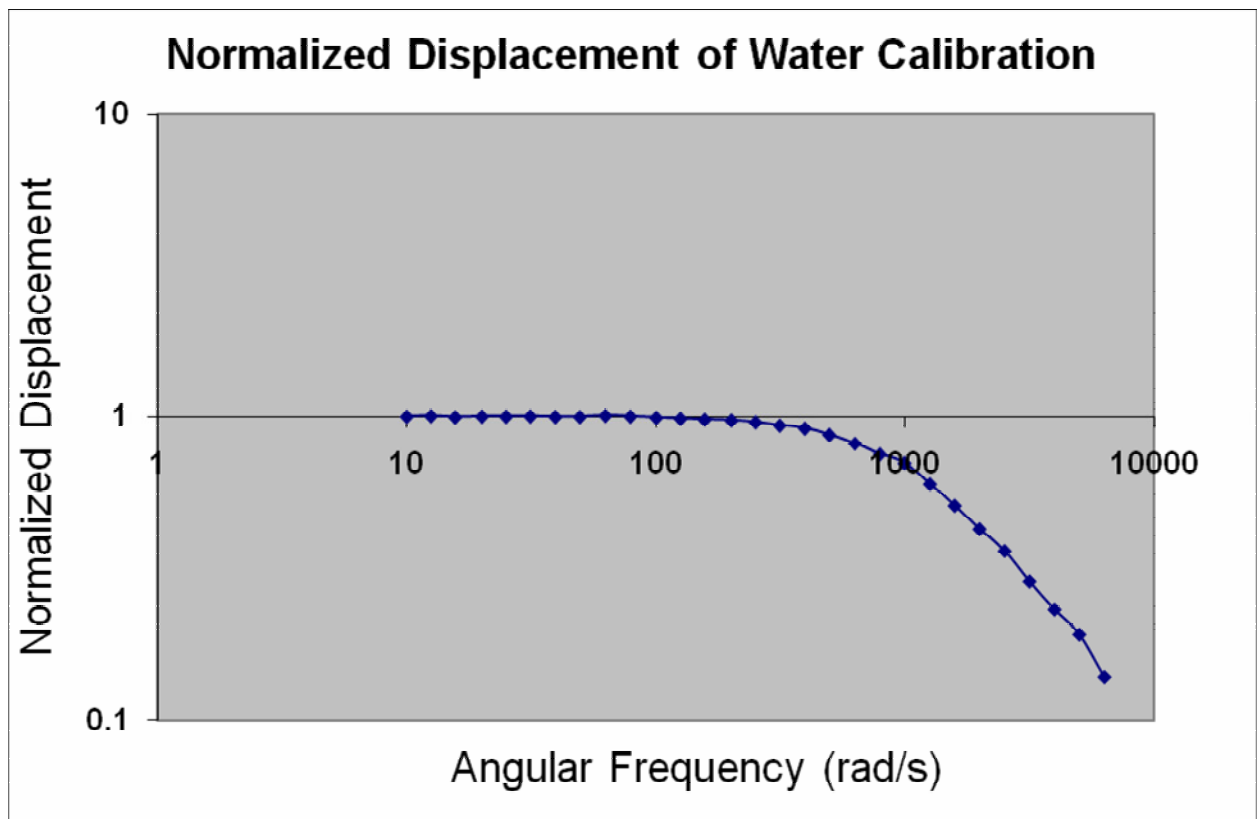
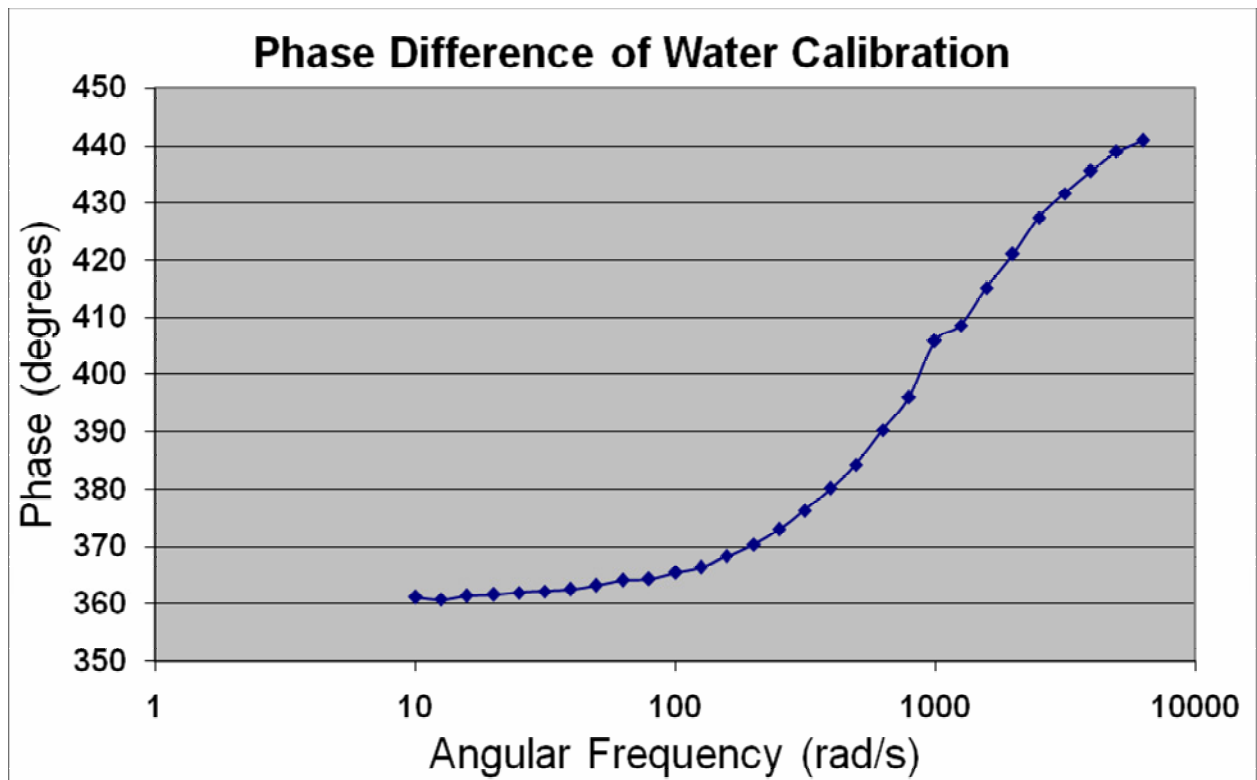
The lasers were kept running throughout the experiment, but the path to the microscope cut off as the samples were being mounted. Once mounted, the sample had to be moved around with an xyz positioned until a bead was pulled into the trap. This was confirmed optically on a monitor displaying the output of the microscope camera. At this point, data was collected by running the labview program, which provided a series of control voltages and frequencies to the piezo-electric mirror as it obtained data from the laser position detector. The data output is in the form of max amplitude of oscillation for a given frequency and the phase difference between the control signal and the response of the bead.

The first objective of the experiment was to calibrate the set-up for measuring the oscillation of 1.5  $\mu\text{m}$  polystyrene beads in water. This provided both a reference for the maximum trap position as well as the trap spring constant.

With this data in hand, a new experiment was run with a 4 weight percent gelatin solution (again imbued with the same polystyrene beads). Using the trap spring constant and the maximum trap oscillation as references, amplitude and phase data could be used to calculate the storage and loss moduli of the gelatin solution.

## Experimental Results and Discussion

From the water calibration the following plots of displacement and phase difference were recorded:



The spring constant of the optical trap itself can be determined from either one of these plots using the formulas:

$$D(\omega) = \frac{A}{\sqrt{\tau^2 \omega^2 + \left(1 - \frac{\omega^2}{\omega_0^2}\right)^2}}$$

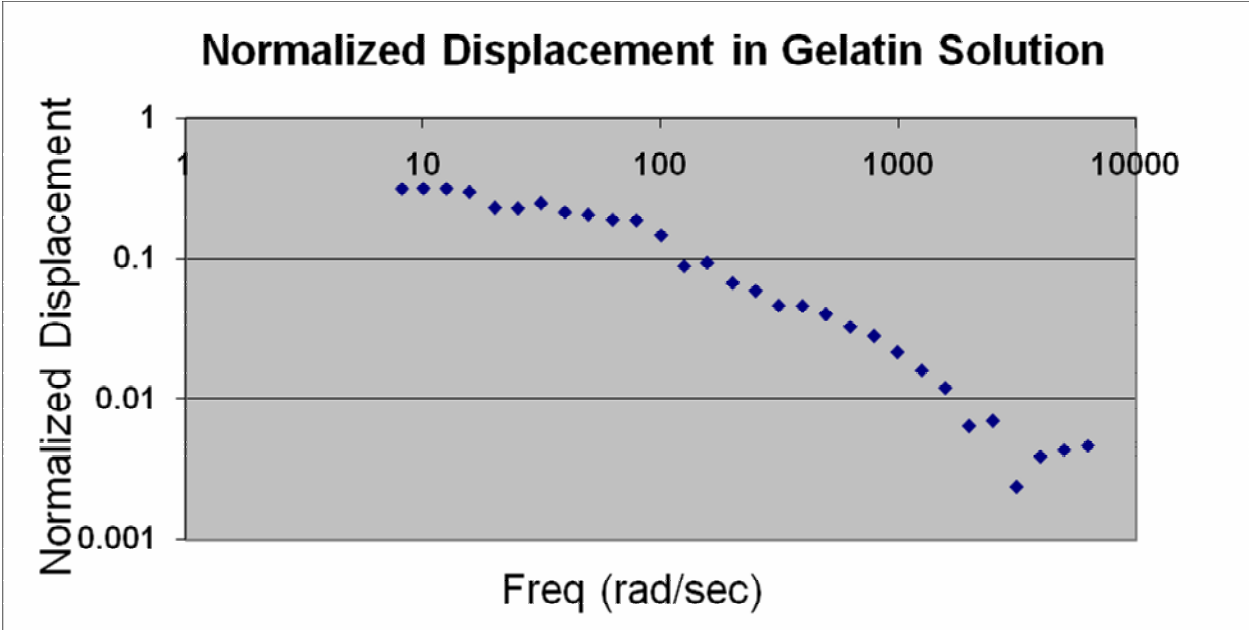
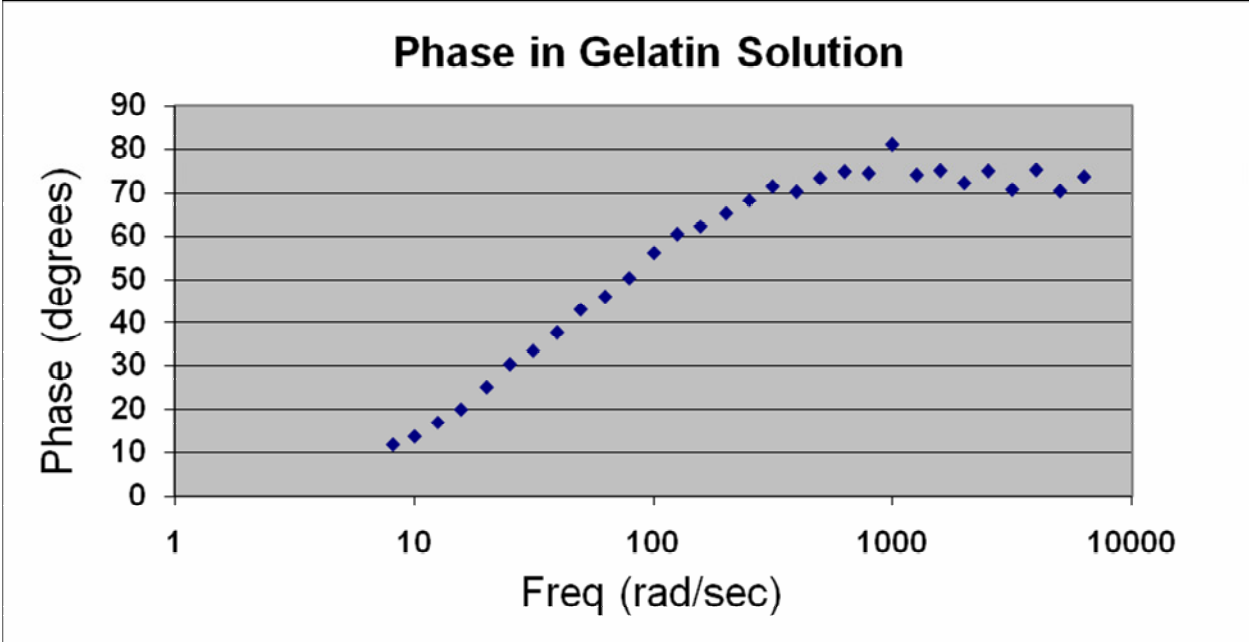
and

$$\delta(\omega) = \tan^{-1} \left( \frac{\tau \omega}{1 - \frac{\omega^2}{\omega_0^2}} \right)$$

where  $\tau = \frac{6\pi\eta_0 a}{k_{opt}}$  and  $\omega_0 = \left(\frac{k_{opt}}{m}\right)^{\frac{1}{2}}$

Fitting the curves according to these formulas provides spring constants of 0.01501 N/m for the phase data and 0.01326 N/m for the displacement. The average of these (0.0141 N/m) is taken for analyzing the gelatin solution. The maximum beam displacement is taken from the raw (not-normalized) displacement data to be 6.273. This is a quantity in units of length, but the units themselves are meaningless since they are a product of the amplified position detector signal. This is why the amplitude data is normalized to this value.

The test was repeated on 2mm x 0.10 mm vitrotube samples of the 4 weight % gelatin solution. Suspended in gelatin, the beads were significantly more difficult to find in order to trap with the tweezers on account of their dispersal throughout the fluid (compared to congregation near the bottom in water). The phase and amplitude data are again recorded, with amplitude normalized to the maximum displacement of the previous calibration.

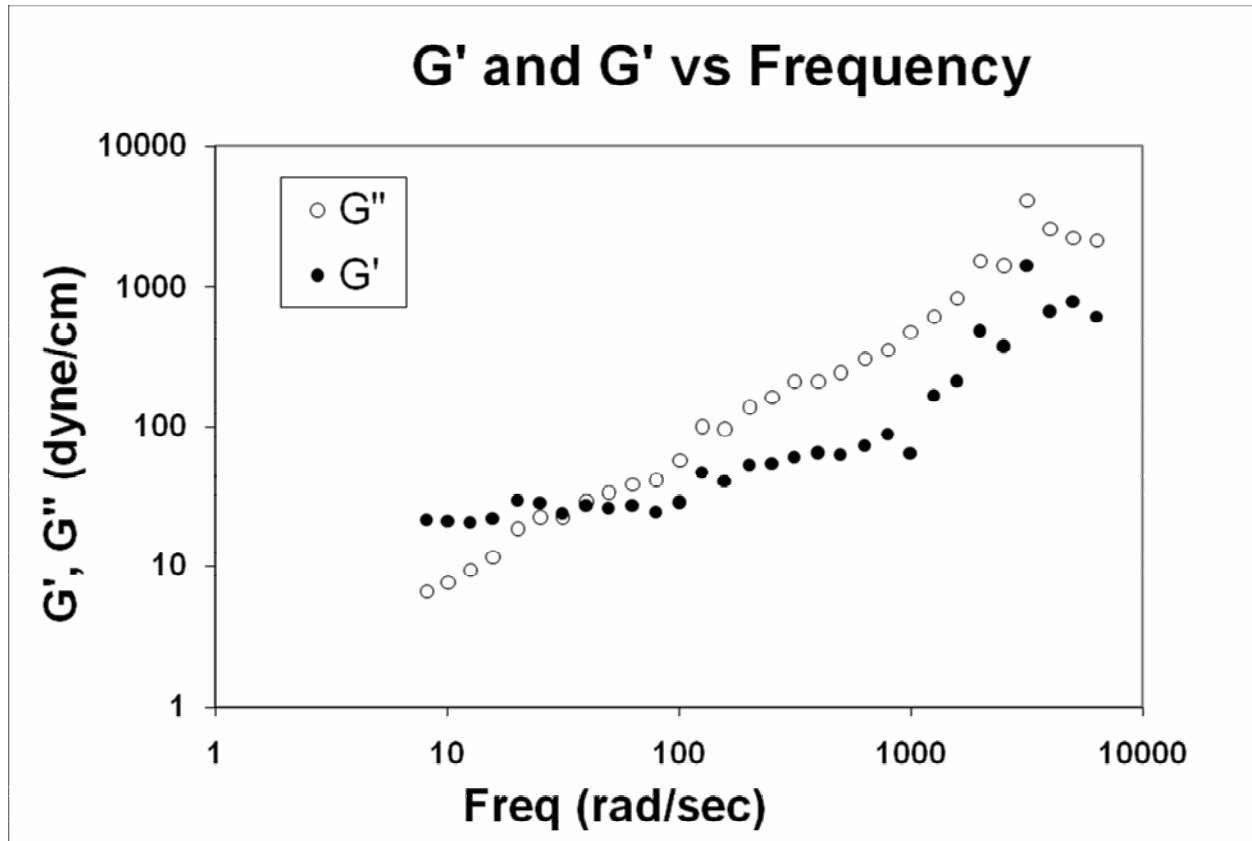


Using the following formulas, this data can be converted into the storage modulus and loss modulus of the gelatin solution. These parameters can be used to generalize and predict the oscillatory behavior of the medium for a range of input frequencies and amplitudes within keeping with the physical assumptions made in determining the model.

$$G' = \frac{k_{\alpha}}{6\pi\eta} \left( \frac{A}{D} \cos \delta - 1 \right)$$

$$G'' = \frac{A}{D} \frac{1}{6\pi\eta} k_{\alpha} \sin \delta$$

Depending upon the amplitude and phase data collected, these parameters are themselves frequency dependent and their values are displayed in the following graph:



### Summary

The spring constant of the laser trap was shown by water calibration to be 0.0141 N/m. This value, along with the max displacement of the beam, was used to generate a plot of the storage and loss moduli for a gelatin solution.