Lab Report
Magnetic Damping

Report by: **Jamie Somers**
Grader: Karsten Fleischer

November 7, 2021

Abstract

The purpose of this experiment was to observe and verify the phenomenon known as magnetic damping and find the damping coefficient b at different field strengths, as well as determine if the magnetic damping was the result of so called "eddy currents" which form when a conductor passes through a magnetic field as stated by Faraday's law of induction and produces a magnetic field in the opposite direction of the conductor as stated by Lenz's law. This was done by recording the displacement of the pendulums angle with respect to time for different magnetic field strengths and fitting the data to a sine wave using guess parameters, one of these parameters being the magnetic damping we are interested in finding. The damping coefficient b of an undamped pendulum was found to be 0.0035, for a field strength of 22.7 ± 0.05 mT $b = 0.03$, for 16.6 ± 0.05 mT b = 0.015 and 7.5 ± 0.05 mT $b = 0.006$. Meanwhile the results of the same measurements with a comb conductor found that there was very little to not damping occurring on the pendulum outside when air resistance is accounted for. These results almost certainly verify Faraday's law of induction and Lenz's law however more research is needed.

1 Introduction

Lenz's Law states that the direction of the electrical current induced in a conductor by a changing magnetic field is such that the magnetic field created by the induced current opposes changes in the initial magnetic field. This law accurately describes what happens when a conductor such as a copper bar passes through a magnetic field. In this experiment a conductor such as a copper bar is attached to a string allowed to tilt on an axis creating a simple pendulum, at the base of the pendulum are two magnets of opposite poles which can have their distance from each other adjusted.

Eddy currents are loops of electrical current induced within conductors by a changing magnetic field in the conductor. This effect is described by Faraday's law of induction. These currents are named after swirling eddies in water streams for their circular motion in closed loops, the eddy currents are induced when there is a change in the flux of a magnetic field and the rotation of the loop will appose the direction which the conductor is moving through the magnetic field.

These continued opposing magnetic field result in a reduction in the kinetic energy of the pendulum, as the non-conservative forces dissipate the energy typically in the form of heat energy. This reduction in kinetic energy due to opposing magnetic fields is whats known as magnetic damping.

2 Background and Theory

The simple harmonic motion of a regular pendulum is well documented within the field of physics and its motion is described mathematically as follows:

$$\frac{d^2\theta}{dt^2} + \frac{g}{l}\sin(\theta) = 0 \tag{1}$$

Where l is the length of the pendulum, g is the acceleration due to gravity, t is time and θ is the angular displacement of the pendulum from its equilibrium position.

The motion of a simple undamped pendulum is so well known that even the angular displacement as a function of time is known mathematically to follow the following equation:

$$\theta(t) = \theta_{max}\sin(\omega t) \tag{2}$$

Where θ_{max} is the maximum angular displacement of the pendulum when it is initially displaced and $\omega = \frac{d\theta}{dt}$ the angular velocity.

In order to accurately describe a damped pendulum, changes have to be made to the above equations. The equation which describes the harmonic motion of a simple damped pendulum is as follows:

$$\frac{d^2\theta}{dt^2} + b\frac{d\theta}{dt} + \frac{g}{l}\sin(\theta) = 0 \tag{3}$$

Where b is the damping coefficient of the pendulum.

The solution to the angular displacement with respect to time for a dampened pendulum is as follows:

$$\theta(t) = e^{-bt}\theta_{max}\sin(\omega t) \tag{4}$$

3 Experimental Design and Procedure

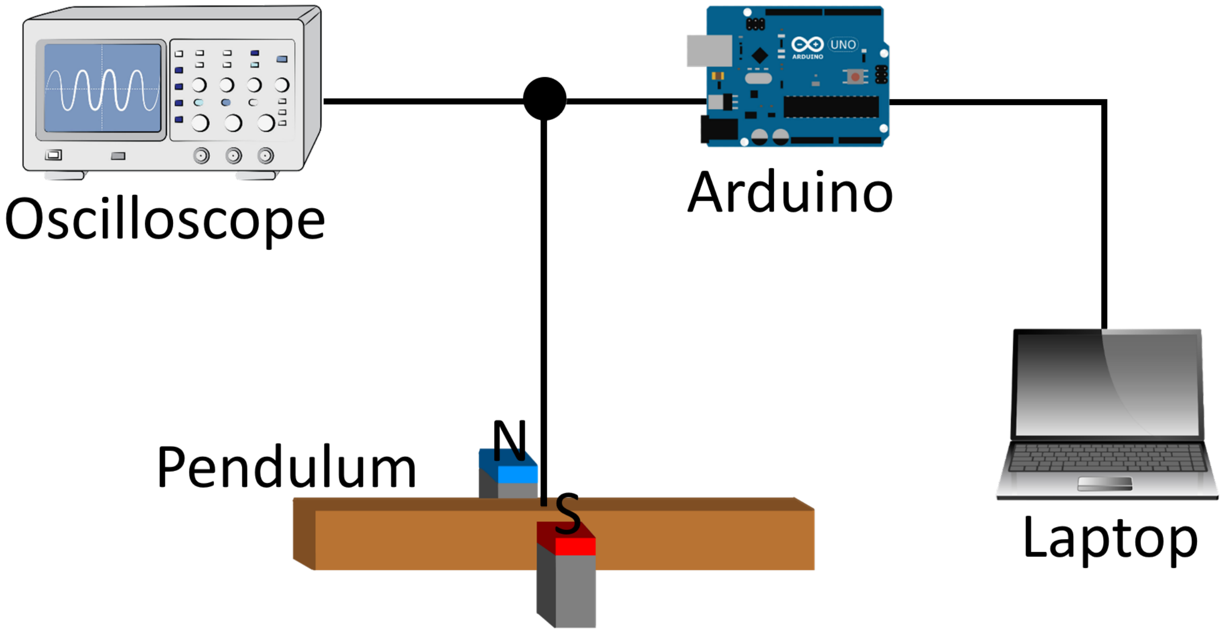

Figure 1: Diagram of experimental set-up for Magnetic Damping experiment

This experimental set-up included a conductor copper bar suspended from a wire which is free to rotate about an axis. An optomechanical angular coder which translates the angle of the pendulum swing into a proportional voltage which is understood by an Arduino using a sketch which can record the 10 values for the angle per second giving us 500 data points for one run. Two magnets either side of the conductor plate with adjustable distances which should directly affect the amount of damping experienced by the pendulum.

In order to begin taking values for the experiment a code must be uploaded to the arduino. The code includes an interrupt subroutine which allows us to take 1 measurement every 10th of a second to an extremely high degree of accuracy. The arduino is connected up to the optomechanical angular coder as well as a start and enable button and an oscilloscope to measure the signal.

Once the code has been uploaded and readings are ready to be measured, predetermined distances of the magnets were chosen and recorded, these will be the distances used throughout the entire experiment for the sake of consistency. The strength of the magnetic field between the magnets at each distance was also measured using a hall probe.

The recording of measurements was started by pressing the enable and begin button for the arduino script to begin taking readings, the pendulum was allowed swing freely with the magnet placed at the base. The initial amplitude of the pendulums swing was chosen such that the pendulum would stay within the field of the magnets for the full cycle. This process was repeated for each of the magnet distances, ensuring to save the data for each measurement.

Finally the copper bar was replaced with a slotted copper bar which is identical in size and width however contains gaps throughout the length of the bar. If the eddy currents really are forming inside the copper bar and damping the pendulum then the slotted bar should produce eddy currents which are much smaller due to the limited space in between the gaps and also the currents should be in opposite directions and cancel out. The slotted bar should not experience the same damping as a result of this.

4 Results

The reference (undamped pendulum) was as follows:

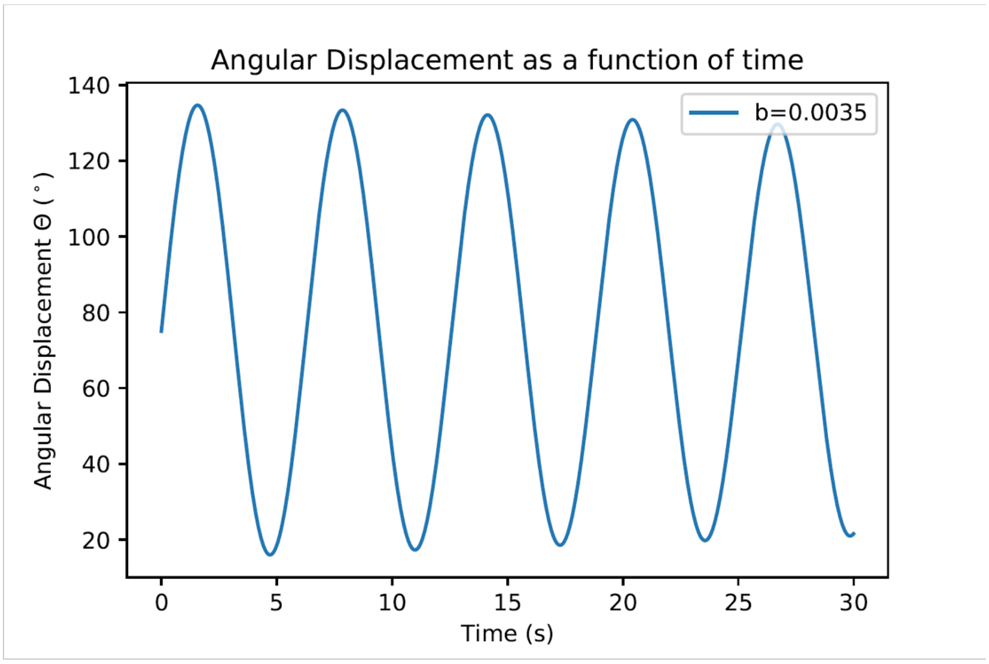

Figure 2: Graph of Angular Displacement θ (°) as a function of time (t).

We can see that the undamped pendulum actually did have a damping coefficient of 0.0035, this damping is most likely due to air resistance and not any error made during the experiment. When pendulums oscillate in a room they experience air resistance which overtime reduces the amplitude that the pendulum can reach, this technically means that every pendulum outside of a vacuum is a damped pendulum.

This will be our reference graph we compare all of our other graphs to, this way we can clearly see the amount of damping occuring due to the magnetic field and the eddy currents and account for air resistance.

The magnetic damping for the pendulum when the magnets were placed 6.0 ± 0.05 cm apart with a magnetic field strength of 22.7 ± 0.05 mT is shown in the graph below:

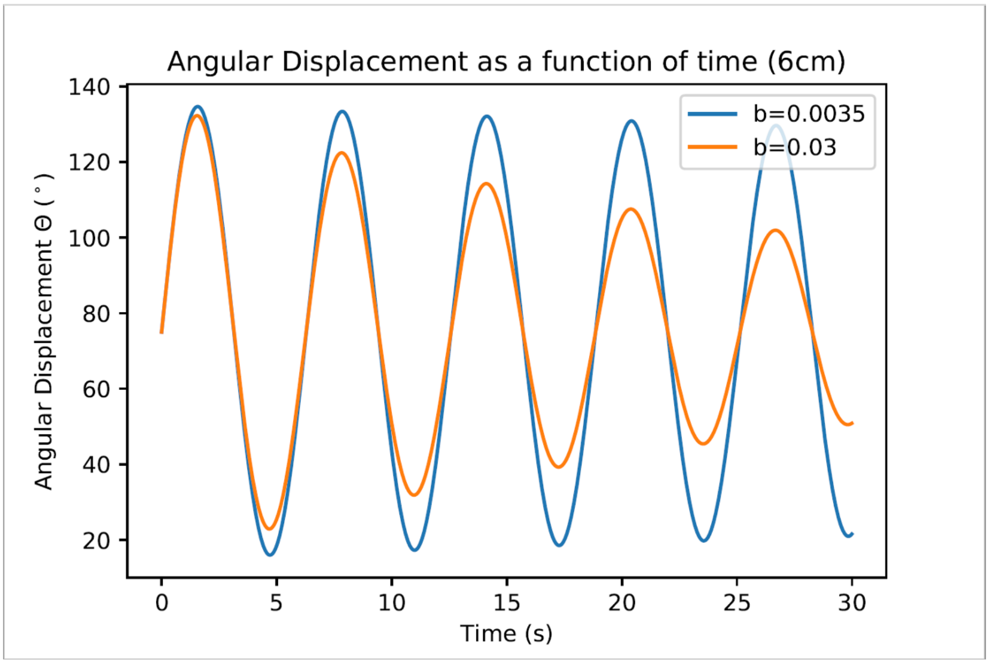

Figure 3: Graph of Angular Displacement θ (°) as a function of time (t).

We see a large amount of damping at 6cm, the closest distance we got to our copper bar, the best fit for our data was a damping coefficient of 0.03 which had a x^2 value of 172998 during our fitting.

We can compare this with the graph for our comb copper conductor and see the affect that damping had on that pendulum.

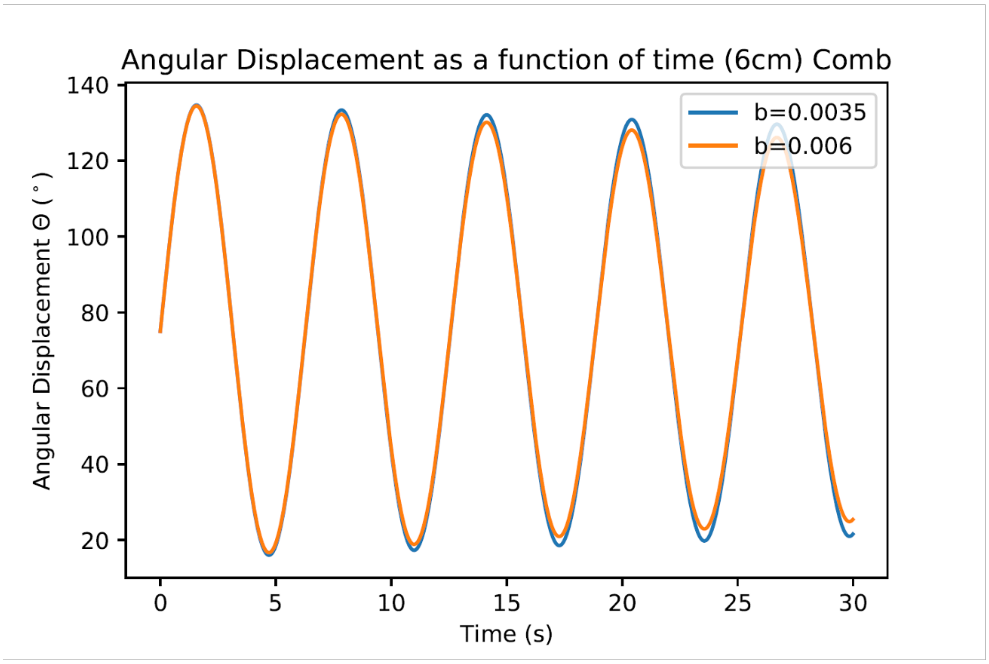

Figure 4: Graph of Angular Displacement θ (°) as a function of time (t).

We can clearly see a much smaller damping occuring which has very little affect on the pendulum for the first couple of oscillations.

We then set the distance between the magnets to be 7.2 ± 0.05 cm apart which was measured to have a magnetic field strength of 16.6 ± 0.05 mT. The angular displacement with respect to time was as follows:

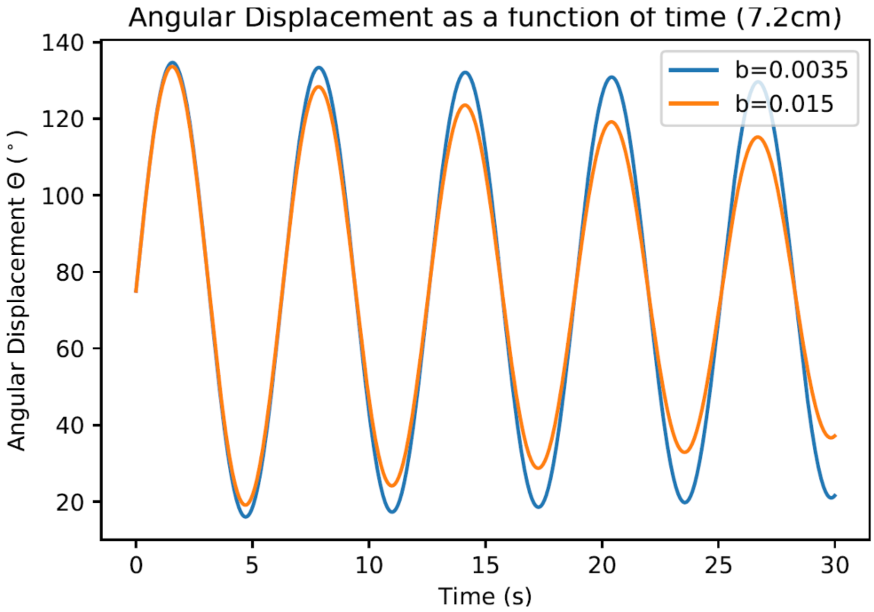

Figure 5: Graph of Angular Displacement θ (°) as a function of time (t).

The graph clearly shows a damping affect occurring with respect to time however the damping coefficient has reduced quite significantly compared to the 6 cm distance. This identifies a strong proportional relationship between the strength of the magnetic field and the damping coefficient.

The same plot for the comb pendulum at 7.2cm is as follows:

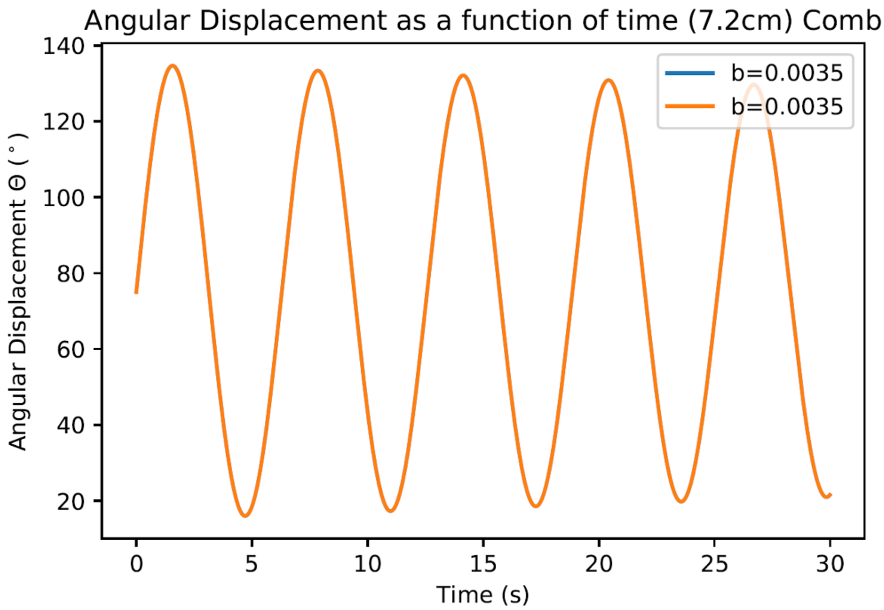

Figure 6: Graph of Angular Displacement θ (°) as a function of time (t).

There is no damping affect seen as the damping coefficient perfectly matches that of the reference pendulum.

Finally we measured a distance of 10.3 ± 0.05 cm between the magnets which corresponded to a magnetic field strength of 7.5 ± 0.05 mT.

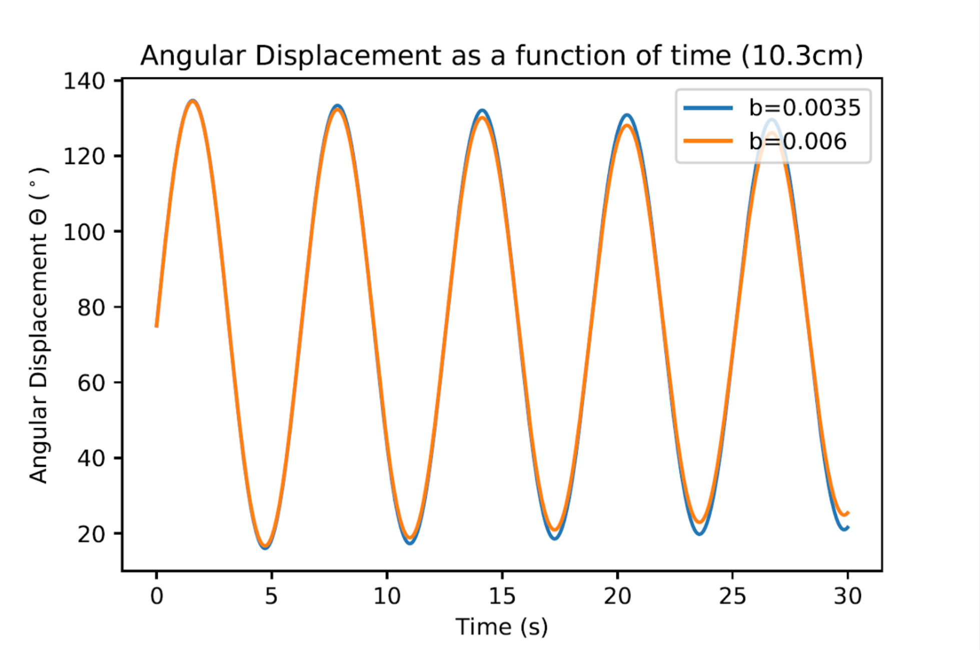

Figure 7: Graph of Angular Displacement θ (°) as a function of time (t).

At this distance we see that the affect that the magnetic field is having on the pendulum is incredibly small as the damping coefficient reaches a value in the same order of magnitude as the reference coefficient. At this point damping experienced by the pendulum is minimal.

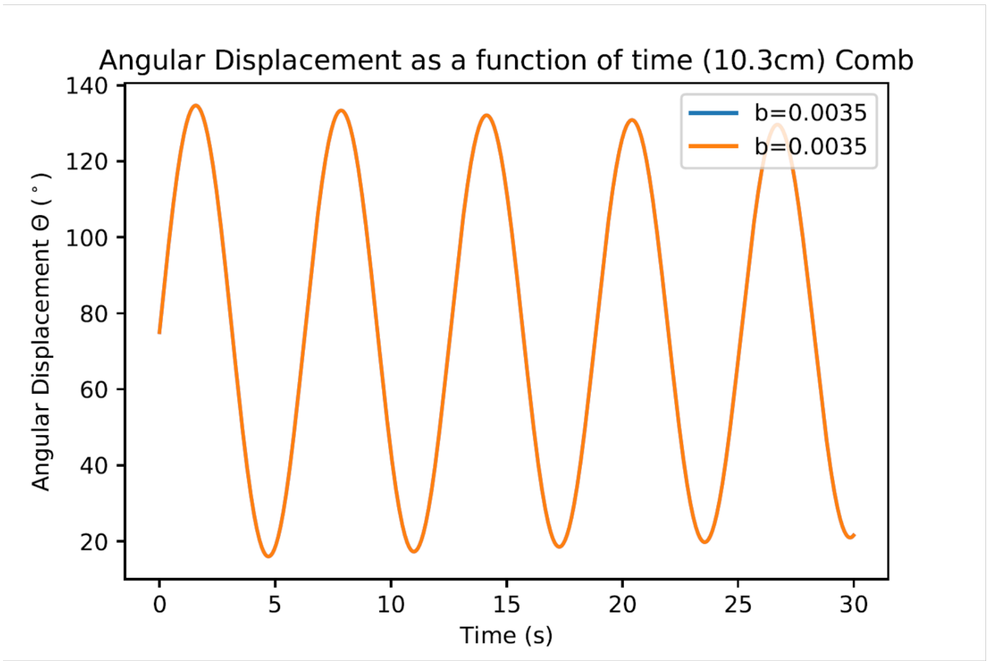

Figure 8: Graph of Angular Displacement θ (°) as a function of time (t).

Once again the damping coefficient for the comb is identical to that of the reference coefficient implying that the comb pendulum is not experiencing any damping from the magnets or eddy currents.

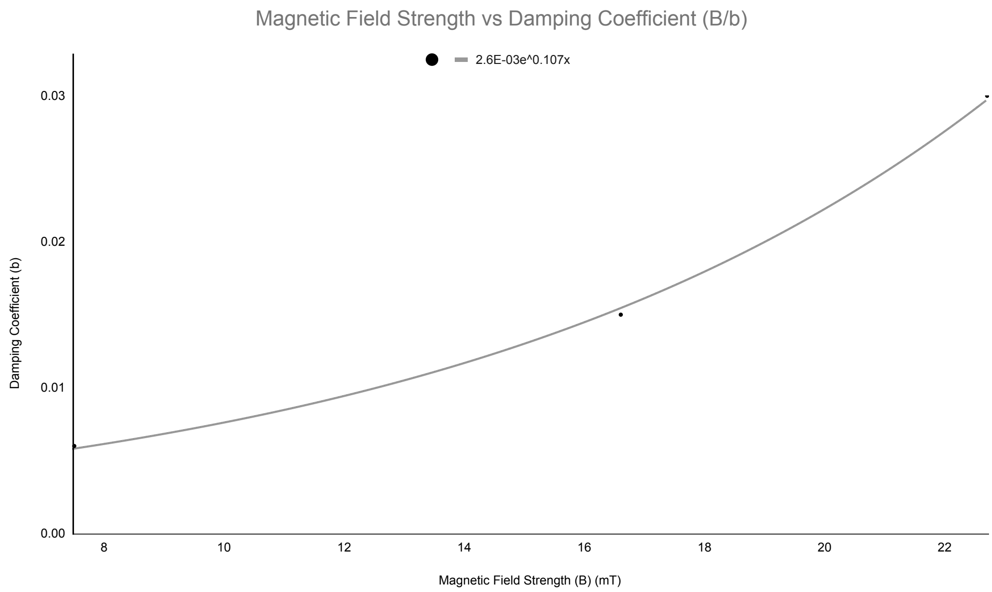

Figure 9: Magnetic Field Strength (B) (mT) as a function of Damping Coefficient (b).

This graph shows that the Damping Coefficient increases exponentially with an increasing Magnetic Field Strength.

5 Discussion and Conclusion

One of the most noticeable errors with the set-up of this experiment is that it is not done within a vacuum. When ”non-damped” pendulums are allowed to freely oscillate about an axis there is still some damping being done by the air resistance acting against the motion of the pendulum. This would explain how we were about to fit our data for an undamped pendulum to a sin wave with a damping coefficient of 0.0035. In order to achieve a perfect undamped pendulum graph where the amplitude remains constant all of the air molecules would have to be removed from the system such as in a vacuum. If this experiment was to be repeated to improve accuracy the pendulum apparatus should be enclosed in a vacuum chamber during the course of the measurements.

The Comb Pendulum plot for when the magnets were 6cm apart implies that there is some small amount of damping occurring that cannot be accounted for with air resistance. In order to be consistent with theory and our other results there should be no damping on any of the comb runs, this is most likely due to some error in the measurement which caused the pendulum to lose amplitude much sooner than it should have. In order to definitively say whether or not the comb pendulum experiences damping with magnets placed at a distance of 6 cm this measurement should be redone multiple times and see if a damping coefficient of 0.006 is consistent throughout.

Despite the damping due to air resistance being a constant throughout the experiment and the unexpected damping coefficient of the comb pendulum with a magnetic field of 22.7 ± 0.05 mT, we can confidently say that passing a conductor through a magnetic field does in fact result in magnetic damping which reduces the amplitude of the pendulums oscillations exponentially over time. It can also be confidently stated that the use of a comb conductor does greatly reduce if not completely eliminates the affect of magnetic damping on the pendulum. This verification of magnetic damping and the conditions needed for magnetic damping to occur support the theoretical explanation for magnetic damping, notably eddy currents and the results of Faraday's law of induction and Lenz's law.