Resisting Motion with Eddy Currents

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This experiment explores the fascinating phenomenon of magnetic damping, where motion is resisted through magnetic fields *without direct contact*. These fields are produced by electric currents induced by changing fields, known as 'eddy currents'. Magnetic suspension systems, such as those used in maglev trains, use the interaction of magnetic fields to levitate and stabilize objects. But how do these systems work? For example, why does a current flow in the secondary winding of a transformer without any direct contact with voltage source? And how do modern transportation systems, like trains and roller coasters, generate braking forces without having any physical contact?

To answer these questions, we turn to the fundamental principles of electromagnetism, particularly Faraday's law of induction, which describes how a changing magnetic flux Φ induces an electromotive force (emf),

$$\varepsilon = -\frac{d\Phi}{dt}. \tag{1}$$

Through this experiment, we investigate how magnetic fields can be used to generate braking forces, shedding light on the underlying science behind non-contact systems in modern technology.

KEYWORDS

Electromagnet · Magnetic Flux · Eddy Currents · Induced EMF · Pendulum · Damping coefficient

1 Objectives

In this experiment, we will

1. understand and observe pendulum motion,
2. Observe and quantify damping of pendulum motion,
3. appreciate one of the four fundamental laws of electromagnetism,

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4. observe the interplay of magnetic fields, flux, electromagnetic induction and mechanical action, and finally,
5. learn how to measure magnetic field and angles using modern sensors.

2 Introduction

2.1 Electromagnets

An electromagnet is a type of magnet in which the magnetic field is produced by an electric current. Unlike permanent magnets, which generate a constant magnetic field, electromagnets can be turned on or off by controlling the electric current.

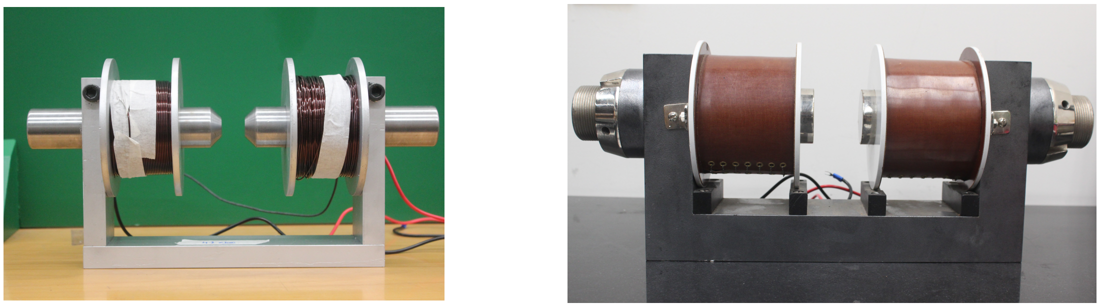


Figure 1: Two kinds of electromagnets used in PhysLab.

2.1.1 Magnetic Field B and Magnetic Flux Φ

Around 1821, Oersted found that a current-carrying conductor produces a magnetic field. In the twentieth century, scientists determined the configuration of elementary particles in atoms and realized that electrons inside atoms also produce tiny magnetic fields. The magnetic field is mapped out by the concept of magnetic field lines. Magnetic field lines are like stretched rubber bands, closely packed near the poles [1]. This is why the closer we get to the poles of a magnet, the higher the magnetic field.

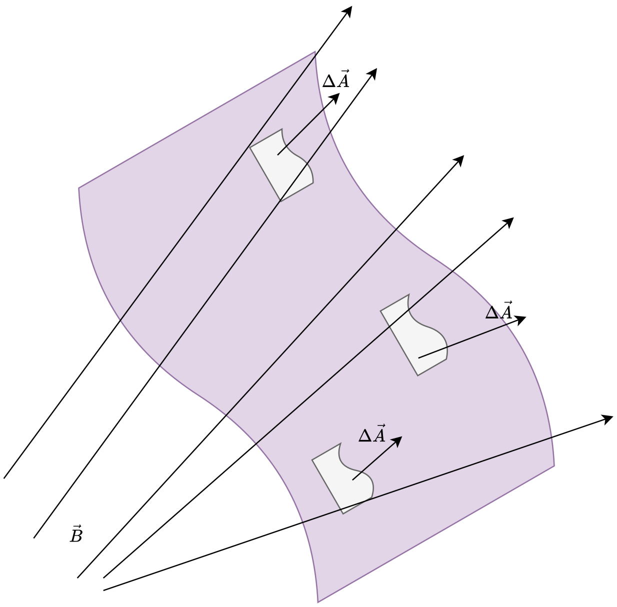


Figure 2: Magnetic field lines passing through an arbitrary shape, illustrating the field's interaction with the region.

The number of magnetic field lines passing through an area is known as the magnetic flux Φ. Consider the arbitrarily shaped surface shown in Figure (2) immersed inside a magnetic field $\vec{B}$. We want to find the flux through identical area elements $\Delta\vec{A}$ perpendicular and away from the surface. A scalar product between the magnetic field vector $\vec{B}$ and each element $\Delta\vec{A}$ is formed and summed to give:

$$\Phi = \vec{B}_1 \cdot \Delta\vec{A}_1 + \vec{B}_2 \cdot \Delta\vec{A}_2 + \cdots \tag{2}$$

which can also be written as:

$$\Phi = \sum_i \vec{B}_i \cdot \Delta\vec{A}_i, \tag{3}$$

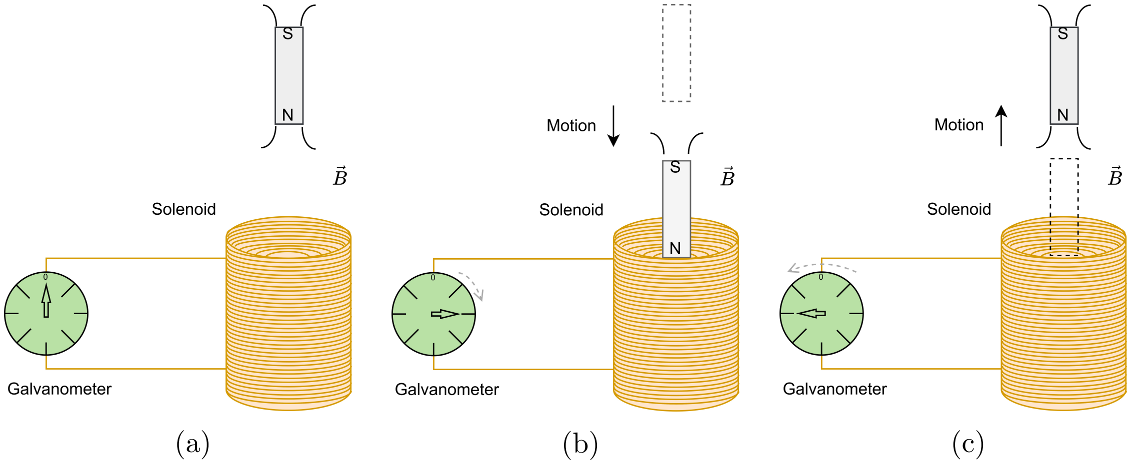
and in the limit of infinitesimal area elements, the flux is:

$$\Phi = \int \vec{B} \cdot d\vec{A} \tag{4}$$

which is an integral over all the small patches that makes up the overall surface.

2.1.2 Electromagnetic Induction

Extensive work was done on current-carrying conductors in the nineteenth century, with major groundwork set by Faraday (1831) and later by Lenz (1834) [2]. Faraday, one of the greatest practical physicists of all times, discovered that a changing magnetic field across a conductor generates an electric field. When a charge is able to move around a closed circuit, the induced field does work on the charge. Similar to the electromotive force (EMF) of a battery, this induced EMF is capable of driving a current around the circuit. which can for example light a bulb or drive a motor.



(a) (b) (c)

Figure 3: Induced EMF in a solenoid. (*a*) No EMF is generated when the magnet is away, whereas (*b*) its movement toward the solenoid induces EMF due to changing magnetic flux, while (*c*) the magnet moving out of the solenoid induces an EMF in the opposite direction, generating a current that opposes the decrease in magnetic flux, as per Lenz's Law.

Faraday's law asserts that the EMF produced is directly proportional to the rate at which the magnetic field lines per unit area, or magnetic flux, 'cut' the conducting loop. Lenz's law is incorporated into Faraday's law through a negative sign, indicating that the EMF produced opposes the relative motion between the conductor and magnet, resisting the change in flux. Mathematically, both of these laws are expressed together as:

$$\varepsilon = -\frac{d\Phi}{dt} \tag{5}$$

for a single loop of conductor, where ε is the electromotive force induced, and Φ is the magnetic flux. The term $d\Phi/dt$ represents the time rate of change of magnetic flux. The rate depends on the speed at which the magnet moves relative to the conductor loop, as well as the strength of the magnetic field. This principle is illustrated in Figure 3, and adapted from [3].

Electric power plants, or more commonly, generators, are a physical manifestation of the laws of induction. The principle is to change the magnetic flux over large stationary coils. The 'change' in flux is brought about mechanically, for example, by falling water or by running a turbine. The changing flux induces an EMF in the coils. This EMF is the source of electricity that turns the wheels of life.

Q 1. What are the units of ε and Φ?

Q 2. Rewrite Equation (5) for N number of loops that are wound to form the coil. How does the ε depend on N?

2.2 Eddy Currents in Solid and Perforated Discs

Eddy currents are loops of electric current induced within a conductor when it is exposed to a changing magnetic field. These currents circulate within the conductor and generate their own magnetic field, which opposes the change in the original magnetic field according to Lenz's law. This phenomenon often results in energy dissipation in the form of heat.

In the context of magnetic braking, the behavior of eddy currents differs significantly between solid and perforated discs:

Solid Disc: In a solid disc, eddy currents can flow freely in large, continuous loops due to the absence of interruptions in the conductive material. The strength of the eddy currents is high, leading to a strong opposing magnetic field and a significant braking force.

Perforated Disc: In a perforated disc, the presence of holes or slots disrupts the path of eddy currents, reducing their size and magnitude. Eddy currents are confined to smaller loops around the holes, which limits their overall strength. This results in a weaker braking force.

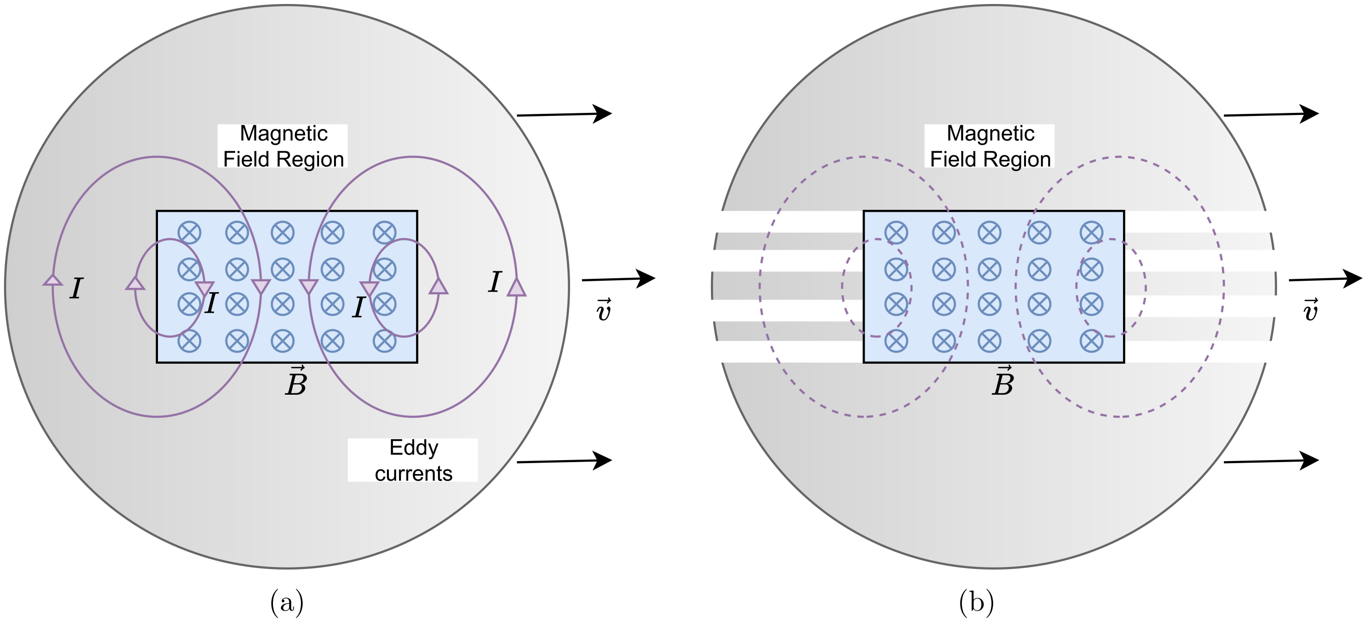


Figure 4: Eddy currents form in the solid disc (a), causing electromagnetic damping, while (b) the perforated disc prevents or limits their generation, slowing down damping, adapted from [3]. In each case the disc is metallic. The solid arrows depict the direction of the moving disc inside the magnetic field.

2.3 Damping

Damping is the process by which oscillations gradually decrease due to resistive forces such as friction or air resistance. It prevents indefinite oscillations and helps systems return to equilibrium. Generally, the amplitude of oscillations in a damped system typically follows an exponential decay, characterized by a gradual reduction in magnitude over time. This decay of $x(t)$ is described by the equation:

$$x(t) = A_0 e^{-\gamma t} \tag{6}$$

where A_0 is the initial amplitude, γ is the damping coefficient, and t is time. Based on the damping strength, it can be of three kinds:

Underdamping: Imagine a child on a swing—gradually slowing down due to friction but still oscillating before stopping. The system oscillates with decreasing amplitude,

$$x(t) = A_0 e^{-\gamma t} \cos(\omega_d t + \phi) \tag{7}$$

where γ is the damping coefficient, $\omega_0 = \sqrt{g/L}$ is the natural angular frequency and $\omega_d = \sqrt{\omega_0^2 - \gamma^2}$ is the damped frequency.

Critical Damping: Think of a car's shock absorbers—after hitting a bump, the car quickly settles without bouncing. The system returns to equilibrium in the shortest time without oscillations, and dynamics can be expressed as

$$x(t) = (A + Bt)e^{-\gamma t} \tag{8}$$

where $\gamma = \omega_0$ ensures no oscillations and the fastest response.

Overdamping: Consider a hydraulic door closer—when pushed, it moves slowly and steadily without bouncing. The system returns to equilibrium without oscillating but takes longer than a critically damped system.

$$x(t) = Ae^{-\gamma_1 t} + Be^{-\gamma_2 t} \tag{9}$$

where $\gamma > \omega_0$, causing a slow, non-oscillatory response.

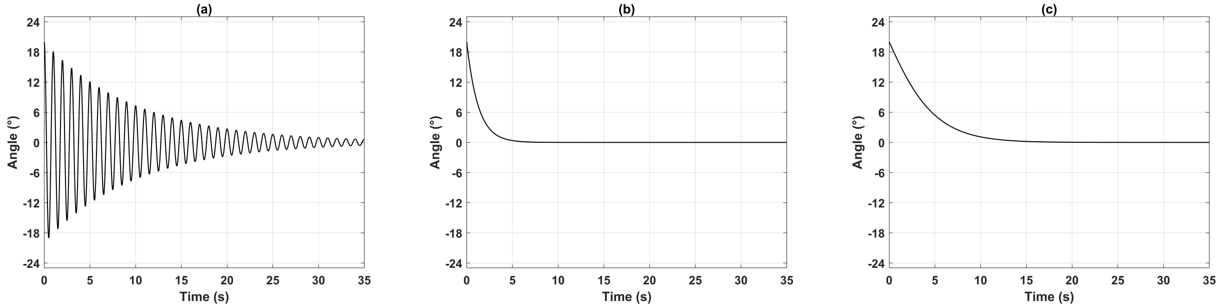


Figure 5: Comparison of responses of (a) an underdamped system, (b) critically damped system and (c) overdamped system.

3 The experiment

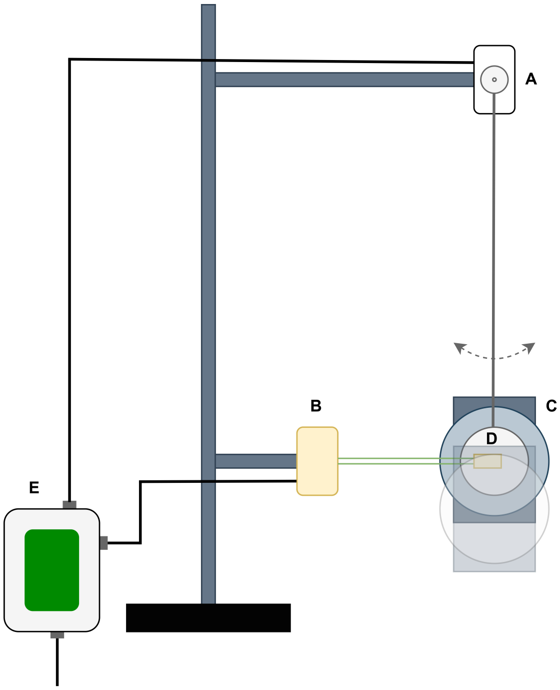


Figure 6: The experimental setup, comprising A: the PhysCompass, B: the PhysHall, C: the Electromagnet, D: Disc, and E: the Physlogger.

Figure 6 is a scheme of the experiment while Figure 7 is a real photograph. This experiment examines the oscillatory motion of a pendulum with solid or perforated discs attached at one end (D), while the other end is connected to a PhysCompass or rotary sensor (A). A PhysHall or Gauss meter (B) measures the static magnetic field between the iron poles of an electromagnet. Both sensors fixed using a retort stand. Data acquisition is managed via the PhysLogger (E), which records measurements from the PhysCompass and PhysHall [4]. The rotary sensor tracks the pendulum's angular displacement (θ), while the magnetic field sensor is positioned between the iron cores without obstructing motion.

These sensors transmit data to a computer running the PhysLogger Desktop App for real-time analysis. A typical live plot is shown in Figure 8. Analyzing these signals helps assess the interaction between the pendulum and the magnetic field. The data is processed in MATLAB a similar software to determine the damping coefficient (γ) and evaluate the system's dynamic behavior.

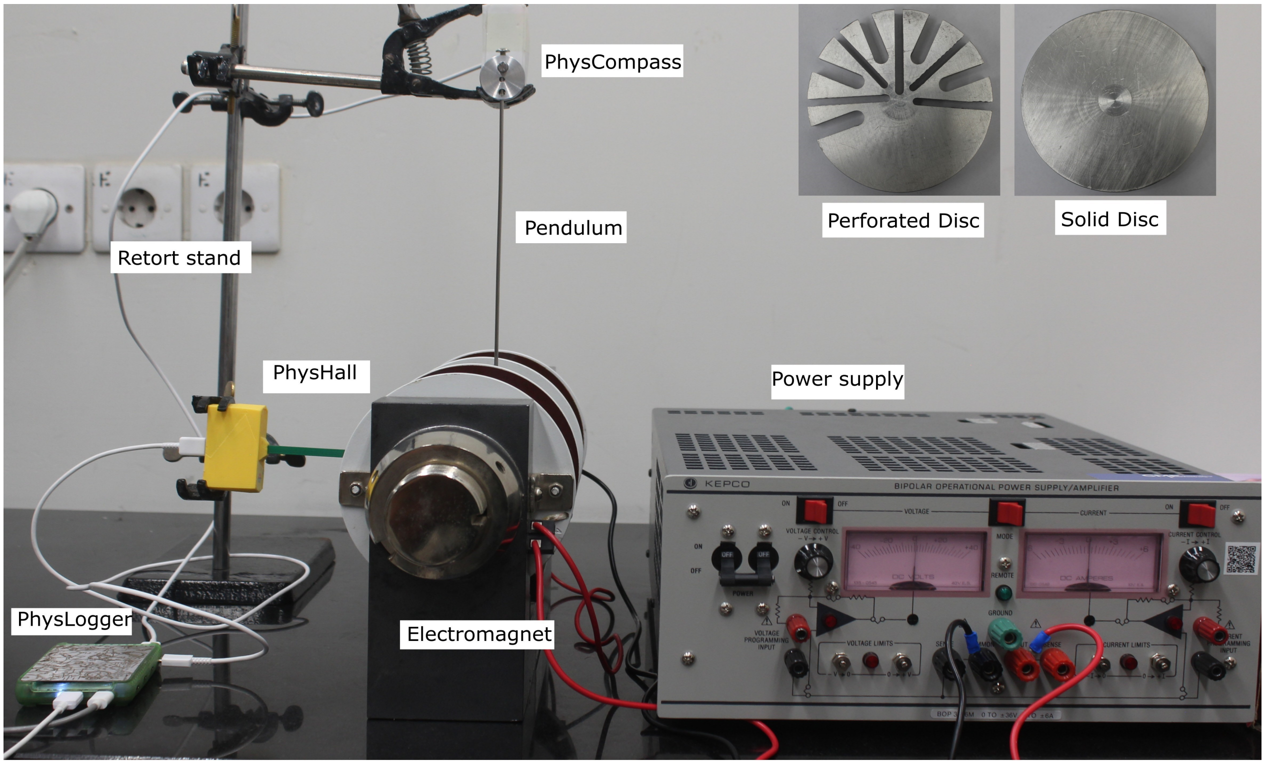


Figure 7: Photograph of the experimental arrangement. The inset on top right shows various possible kinds of solid and perforated discs employed.

3.1 Physical characteristics of the pendulum

Table (1) provides a comparison of the physical characteristics of two types of pendulums used in the experiment.

	Solid disc	Perforated disc
Diameter	7.6 cm	7.6 cm
Weight	130 g	99 g
Material	Aluminum	Aluminum
Length of Pendulum	25 cm	25 cm

Table 1: Physical characteristics of the two kinds of discs.

3.2 Preparing for the experiment

Before starting the experiment, we make sure to verify the following aspects.

1. Attach the PhysCompass and the PhysHall to retort stand with the help of clamps such that they placed between the iron cores.

2. The pendulum is tightened to the rotary sensor. Tightening prevents it from the slight

to and fro motion. It increases mechanical efficiency and allows for more accurate data collection.

3. The orientation of the pendulum should be such that its motion is free of interference (either by PhysHall or iron cores).

4. All connections are made, as shown in Figure 4.

5. Try to clean the area around the power supply and the electromagnet, especially the metal items to ensure safety.

6. Notes about configuring PhysLogger:

    - It is connected to the PC via a USB cable.
    - It is connected to the PhysCompass via one of its digital channels and to the PhysHall via one of its analog channels. When all these preparations are made and PhysLogger is responding to changes in the pendulum's movement, the apparatus is ready for experimentation.

3.3 Conducting the experiment

1. In the PhysLogger Desktop App, select `Measure` > `Rotation and magnetic flux`. Make a live plot. (PhysCompass should have already been connected to PhysLogger before starting the App).

2. Go to `Quantities Panel` > `PhysCompass` and set the units of angular measurements to degrees. When the pendulum is stationary at its equilibrium position, tare the readings of PhysCompass.

3. Similarly, go to `Quantities Panel` > `PhysHall` and set the units of magnetic flux to Gauss.

4. Set a desirable sampling rate, such as 100 Hz. (Try to maintain it throughout the experiment)

5. Once you are ready to begin the experiment, click on Clear Plots and nudge one side of the pendulum.

6. The pendulum will begin to oscillate, and the angular data and the applied flux detected by PhysLogger are sent to the computer. A sample plot is shown in Figure 8.

7. Once the data has been collected, `Save all quantities` > `Show in Explorer`. Now the data can be analyze using MATLAB, Python, or any software.

    (Note: Ensure that the power supply is turned off after each reading to prevent overheating of the electromagnet.)

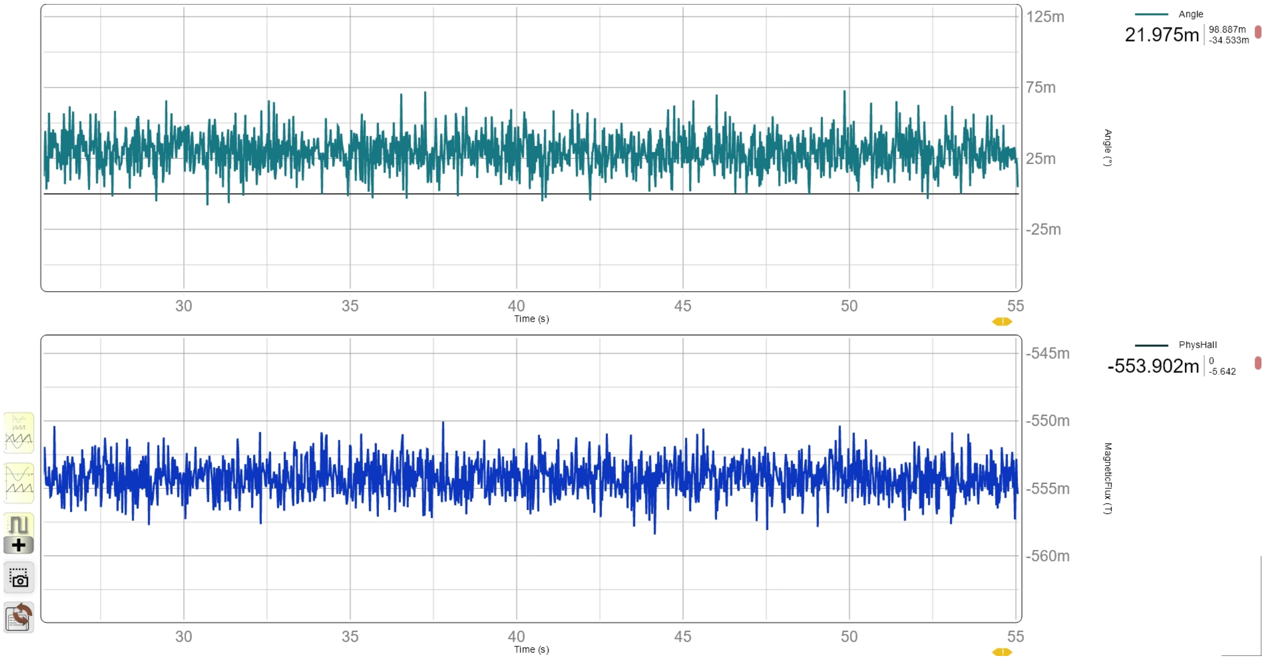


Figure 8: Sample data from PhysCompass and PhysHall.

4 The data

Conduct experiments to observe the behavior of a pendulum under different damping conditions: underdamping, overdamping, and critical damping. Analyze how solid and perforated discs respond to air friction and magnetic damping.

Q 3. Using your recorded data, plot graphs of magnetic field (B) vs. time (s) and angle (θ) vs. time (s) for each case. Analyze the oscillatory behavior of both discs and determine the damping coefficient (γ) using the *Find Peaks* function in MATLAB. Plot peak values separately using the *stem* function and curve fit using $x(t) = A_0 e^{-\gamma t}$.

Q 4. Find the damping coefficient (γ) at various magnetic field (B) values and complete the table below. Ensure that the field remains constant while nudging the pendulum at approximately the same angle for each measurement.

Magnetic Field (G)	γ_{solid} (s^{-1})	$\gamma_{perforated}$ (s^{-1})
500		
750		
1000		
1250		
1500		
1750		
2000		

Table 2: Effect of Magnetic Field on damping coefficient (γ)

Additionally, plot the magnetic field ($\vec{B}$) vs. damping coefficient (γ) and describe the observed trend.

Q 5. Compare the damping effects of the solid and perforated discs. Since the perforated disc has less surface area in the magnetic field, explain why its damping is weaker than that of the solid disc. Discuss the importance of the damping effect in each case and assess its applicability to real-world scenarios.

Q 6. Conduct the same experiment using materials other than aluminum. Analyze how different materials influence oscillatory motion in the presence of a magnetic field based on their conductivity and other characteristics.

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