Electromagnetic Induction and Associated Phenomena

Experimental Objectives

The project involved building an experimental setup to investigate the following for a magnet falling through a tube:

1. The relationship of changing magnetic flux with induced emf in a conductor.
2. Driving a load like light emitting diode using induced emf.
3. Determining the value of gravitational pull ‘g’.
4. Electromagnetic braking through analysis of damping due to induced flux.
5. Eddy current induced in a conductor.

Introduction

Electromagnetic induction stands as a foundational principle in the realm of physics, driving our understanding of the relationship between magnetic fields and electric currents. This phenomenon, explained by Faraday's groundbreaking experiments, has vast applications in various fields, from power generation to magnetic braking systems. The experiment conducted herein seeks to explore and analyze electromagnetic induction through the scenario of a magnet's descent through a pipe.

The phenomenon of electromagnetic induction reveals itself in multifaceted ways during this experiment. As the magnet plunges through the metallic pipe, several interrelated phenomena emerge, including damping effects, electromagnetic braking, induced electromotive force (emf), induced flux, and the generation of eddy currents. Each of these aspects encapsulates the intricate interplay between magnetic fields and electrical currents, providing a nuanced understanding of electromagnetic induction.

The principle equation of electromagnetic induction is Faraday’s law that states that the emf induced in a conductor is equal to the rate of change of magnetic flux through the conductor. Lenz’s law is incorporated in Faraday’s law by introducing a negative sign that shows the magnetic field associated with the emf induced in the conductor opposes the relative motion of the magnet causing the change in flux. These laws are expressed as follows:

$$emf = \varepsilon = -\frac{d\Phi}{dt}$$

where ε is the emf and Φ is magnetic flux which is defined as $\Phi = \int \vec{B}.d\vec{A}$ ($\vec{B}$ = magnetic field vector,

d $\vec{A}$ = infinitesimal area element vector of the surface through which magnetic field lines pass).

The damping observed in this experiment occurs due to the generation of eddy currents, induced within the conducting pipe as a reaction to the changing magnetic flux produced by the descending magnet.

These eddy currents, in turn, create a resisting force, manifesting as the gradual deceleration of the magnet's descent—an effect commonly known as electromagnetic braking. This inter-conversion of mechanical energy into electrical energy exemplifies the foundational principles of electromagnetic induction.

Moreover, the induced electromotive force (emf) and flux alterations experienced during the magnet's motion illustrate the dynamic relationship between magnetic fields and induced currents. The induced emf, resultant from the changing magnetic flux, showcases the ability of electromagnetic induction to induce a potential difference across a circuit without direct physical contact, underscoring its relevance in generating electrical power and understanding transformer operations.

Furthermore, the experiment also aimed to calculate the value of the gravitational force 'g' using the phenomenon of electromagnetic induction. This can be seen as an application of electromagnetic induction in experiments that require accurate time measuring methods.

Thus, this experiment seeks to validate and investigate the theoretical foundations of electromagnetic induction, laying the groundwork for practical applications in engineering and physics.

Apparatus

1. Multiple cylindrical magnets of radius 0.6 cm and mass 19.7 g.
2. Two cylindrical tubes (PVC for non-conducting tube and Copper for conducting tube), preferably of length 1 meter, and diameter 1.3 cm to allow the magnet to fall through the tube while ensuring that magnetic flux is generated.
3. A stand to hold the tube vertically.
4. A long copper wire to make the two solenoids at the ends of the columns.
5. A data acquisition device that samples the induced EMF, and sends the data to a computer (Physlogger). Connecting wires to connect the solenoids to the data logger.
6. PN junction diode: IN4007.

Software

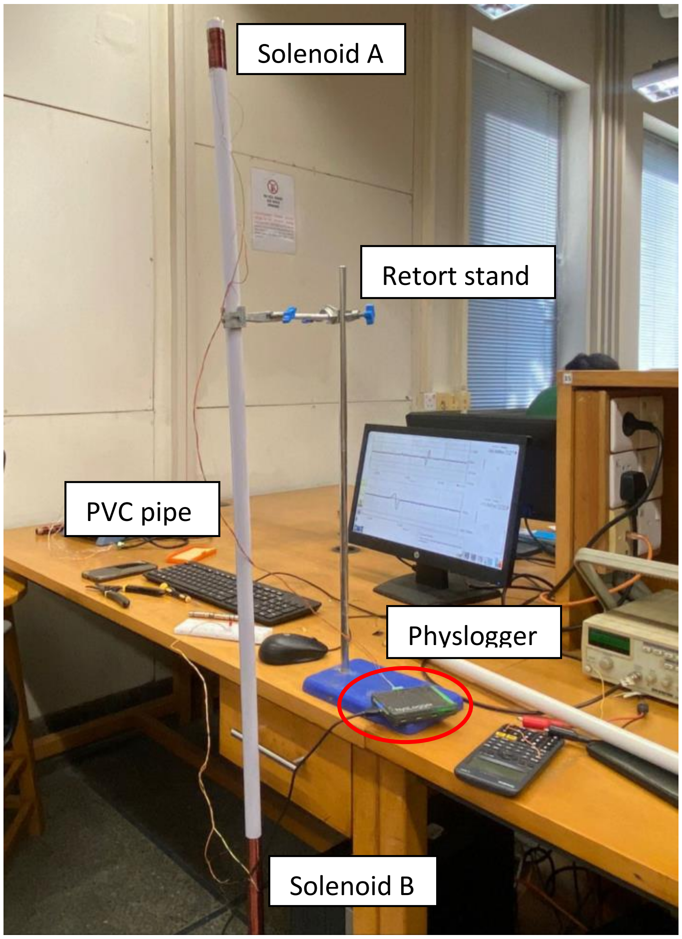
1. Computer software (Physlogger) that links with the data acquisition hardware, and stores as well as plots the results.
2. Matlab: This software will use the data generated by the data acquisition software and do mathematical calculations on it.

A. Calculating value of Gravitational Acceleration ('g')

Purpose

The purpose of this experiment is to find the value of gravitational acceleration by observing induced emf in two solenoids connected to ends of a non-conducting pipe due to a free fall magnet. In addition, the experiment aims to show how induced EMF and magnetic flux change as a magnet is dropped from rest, under uniform acceleration, through the solenoids wrapped around the pipe.

Experimental setup



A copper wire is wrapped on both ends of the PVC tube (length = 1.23m) to create a solenoid at each end. The two ends of each solenoid are soldered to the connecting wires which connect the solenoids to the Physlogger using a circuit board connector. A retort stand is used to hold the pipe vertically as the magnet is dropped inside it.

Procedure

A magnet is released from rest from the top of the pipe. The PhysLogger software records the fluctuation in emf against time as the magnet falls between the two solenoids. From the live plots of the emf fluctuations produced by the PhysLogger, the time difference is taken between the start of the first waveform generated (when the magnet passes through the top of solenoid A) and the midpoint of the second waveform generated (when the magnet passes through the middle of solenoid B).

Three trials were taken.

Value of g is calculated using the equation:

$$\boldsymbol{S = ut + \frac{1}{2}at^2}$$

where:

S = The length of the PVC pipe from the top of the first solenoid to the midpoint of the second;

u = The initial velocity of the magnet (which is zero since the magnet is released from rest);

a = The acceleration of free fall;

t = The time taken by the magnet to fall between the two solenoids (Time difference between the start of the first waveform and the midpoint of the second waveform).

Since u = 0;

$$\boldsymbol{S = \frac{1}{2}at^2}$$

Data Acquisition and Analysis:

$$\boldsymbol{S_{average} = \frac{0.974 + 0.964 + 0953}{3} = 0.964\ m}$$

Trial #	T_1 /s	T_2 /s	$T = T_2 - T_1$ (s)	g (ms^{-2})
1	5.523	5.948	0.425	10.78
2	38.513	38.947	0.434	10.24
3	11.544	11.998	0.454	9.35

$$g = \frac{10.78 + 10.24 + 9.35}{3} = 10.12\ ms^{-2}$$

Uncertainty Analysis

Calculating uncertainty in time T:

Least count of time reading displayed by Physlogger = 0.001 s

$$Type\ B\ uncertainty\ in\ time\ T = \Delta T = \frac{least\ count}{2\sqrt{3}} = \frac{0.001}{2\sqrt{3}} = 3 \times 10^{-4}\ s$$

Calculating uncertainty in length S:

$$Type\ B\ uncertainty\ in\ length\ S = \frac{least\ count}{2\sqrt{6}} = \frac{0.001}{2\sqrt{6}} = 2 \times 10^{-4}\ m$$

$$Type\ A\ uncertainty\ in\ length\ S = \sqrt{\frac{\sum_i^3 (S_i - S_{avg})^2}{2}} \div \sqrt{3} = 6 \times 10^{-3}\ m$$

$$Total\ uncertainty\ in\ length\ S = \Delta S = \sqrt{(2 \times 10^{-4})^2 + (6 \times 10^{-3})^2} = 6 \times 10^{-3} m$$

Propagation of uncertainties in g:

$$\Delta g = \sqrt{\left(\frac{\partial g}{\partial l} \times \Delta S\right)^2 + \left(\frac{\partial g}{\partial T} \times \Delta T\right)^2} = \sqrt{\left(\frac{2}{T^2} \times \Delta S\right)^2 + \left(\frac{-4S}{T^3} \times \Delta T\right)^2}$$

$\Delta g_1 = 7 \times 10^{-2}\ ms^{-2}$

$\Delta g_2 = 7 \times 10^{-2}\ ms^{-2}$

$\Delta g_3 = 6 \times 10^{-2}\ ms^{-2}$

Type A Uncertainty in 'g':

$$\boldsymbol{\Delta g_{avg}} = \sqrt{\frac{\sum_i^3 (g_i - g_{avg})^2}{2}} \div \sqrt{3} = 0.04\ ms^{-2}$$

Type B Uncertainty in 'g':

$$\boldsymbol{\Delta g_B} = \frac{(7 \times 10^{-2}) + (7 \times 10^{-2}) + 6 \times 10^{-2}}{3}$$

Total Uncertainty in 'g':

$$\boldsymbol{\Delta g_{Total}} = \sqrt{(\Delta g_{avg})^2 + (\Delta g_B)^2}$$

$$\boldsymbol{\Delta g_{Total}} = \sqrt{(0.6)^2 + (0.04)^2}$$

$$\boldsymbol{\Delta g_{Total}} = 0.6\ ms^{-2}$$

Value of Gravitational Pull 'g':

$$\boldsymbol{g = (10.12 \pm 0.6)\ ms^{-2}}$$

B. Driving LED

Experimental Setup

a) PVC pipe (1.23m). A copper wire wrapped on both ends to create two solenoids, 1 at each end;

b) The two ends of the solenoids are soldered to the connecting wires which connect the solenoids to the PhysLogger using a connector. The solenoids were then connected to the LED using a breadboard.

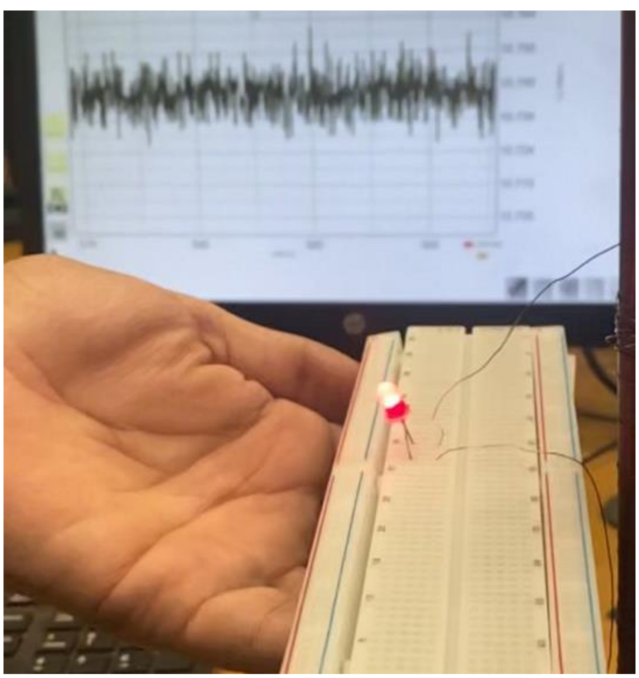
c) A retort stand is used to hold the pipe vertically as the magnet is dropped inside it.

Procedure

Same experimental setup is used as before. Dropping a magnet through the PVC pipe generates a voltage which can be used to drive a light emitting diode LED. The ends of the solenoid at the bottom are connected directly to a breadboard. The LED is also connected to the breadboard. AC voltage is generated; however, no rectifier circuit was used to convert it to DC. This is because 1.5 volts were being generated and connecting a rectifier circuit would have led to 0.7 volts being dropped, and the remaining voltage would not have been enough to drive the LED. The AC voltage did not damage the LED because the peak inverse voltage was less than 5 V. The two ends of the bottom solenoid are then connected to the PhysLogger to generate a live plot of the generated EMF.

Observations

As the magnet is dropped inside the PVC pipe, the LED lights up.



C. Induced flux

Experimental Setup

Same as the set up for the experiment A.

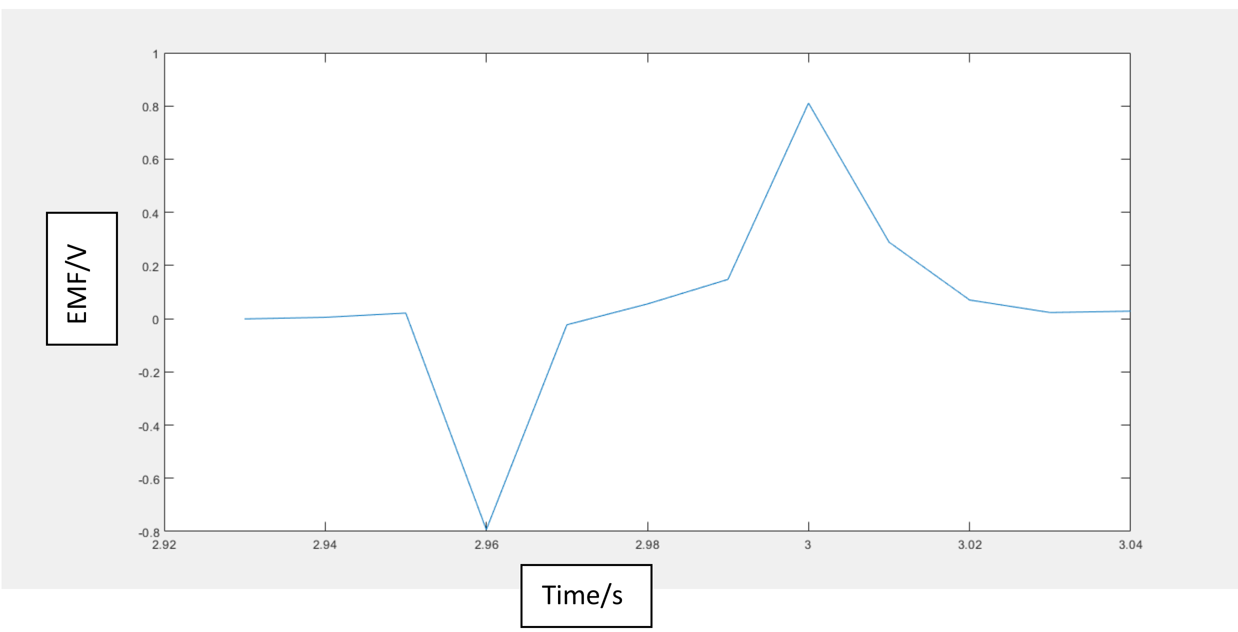
Procedure

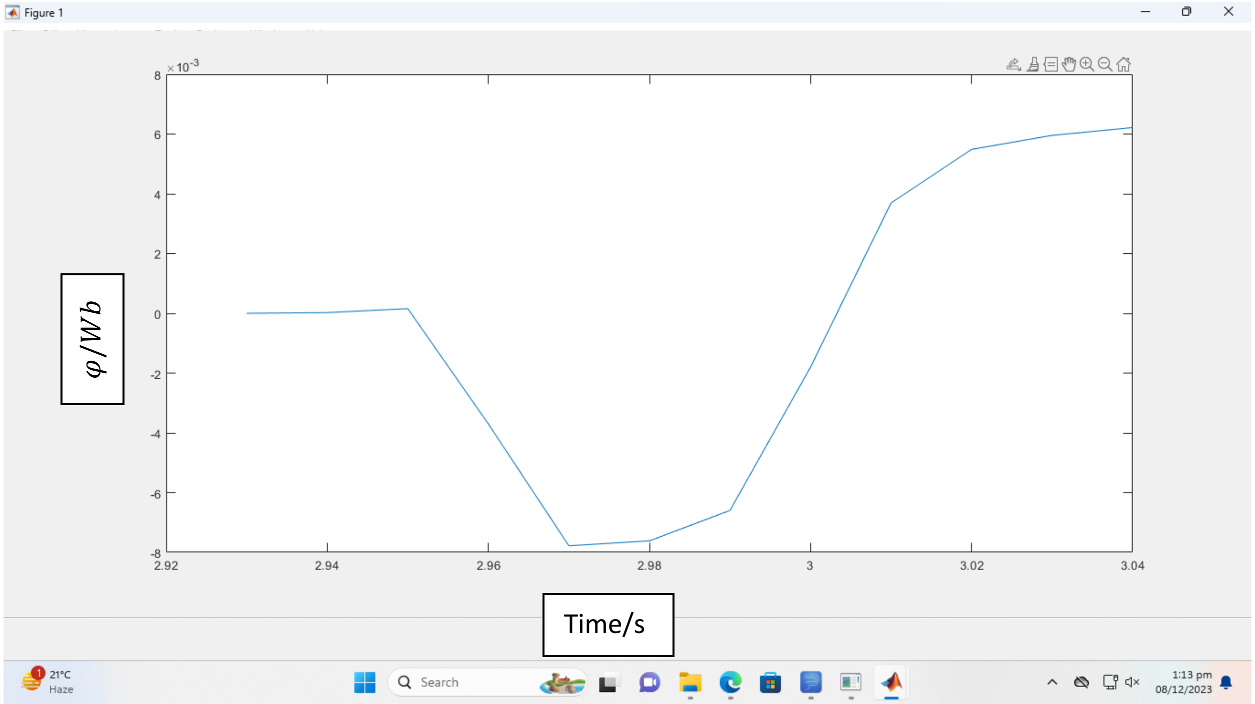
Magnets are dropped from the top of PVC pipe. The voltage/emf generated due to the change in magnetic flux through the solenoids is recorded by Physlogger and a live plot is generated for this emf on the Physlogger software.

This data for emf vs time for each solenoid is imported into the Matlab software and a numerical integration function "cumtrapz" was applied on these data points to obtain the values of magnetic flux and hence, generate a corresponding graph for magnetic flux vs time.

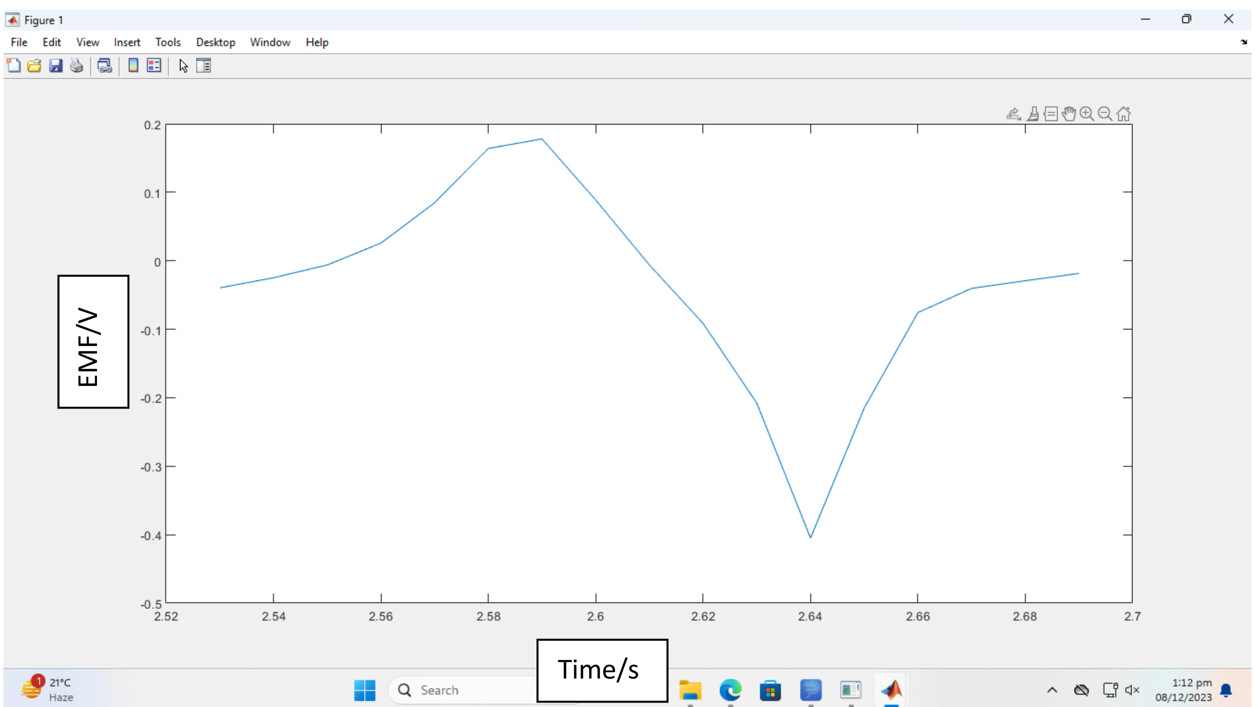
Obtained Results

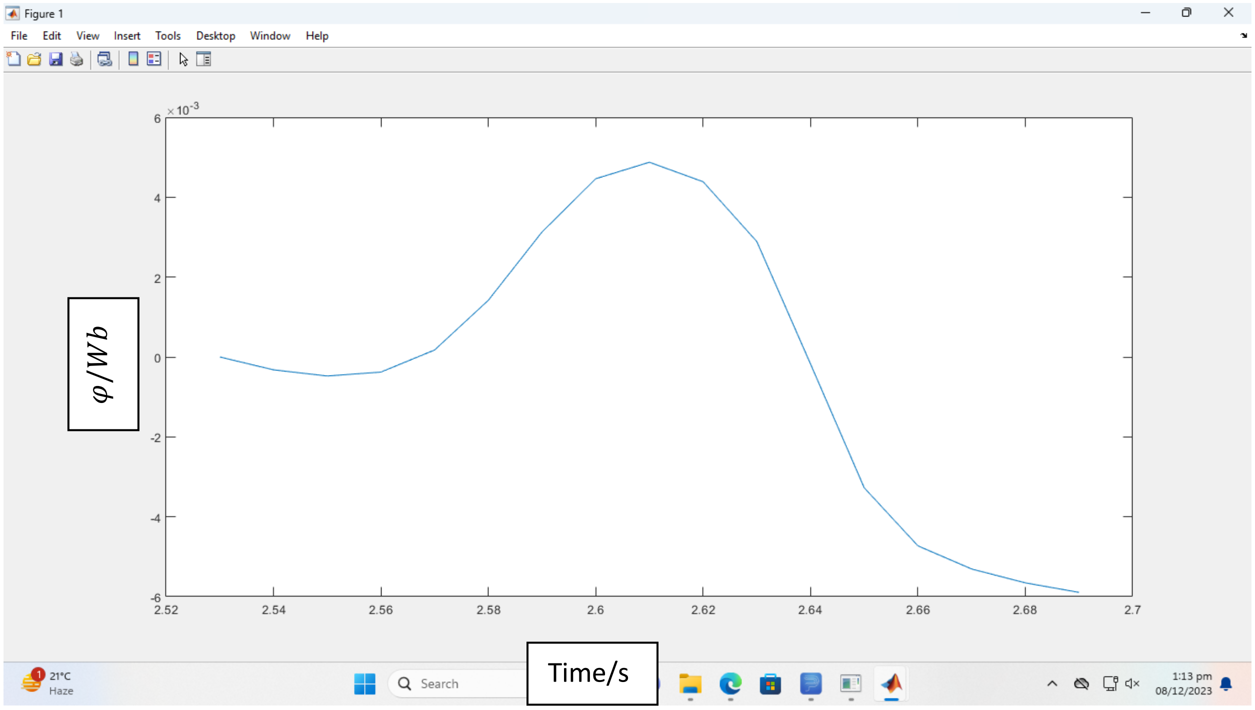
First Solenoid:





Second Solenoid:





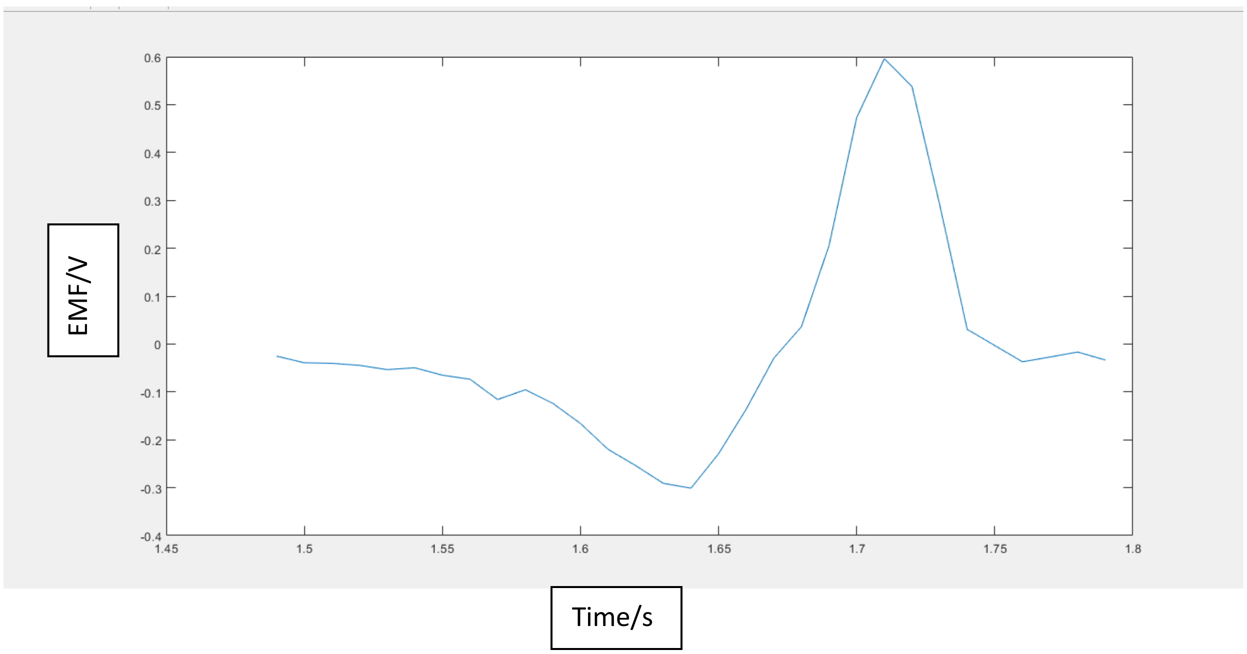
D. Increasing the induced flux

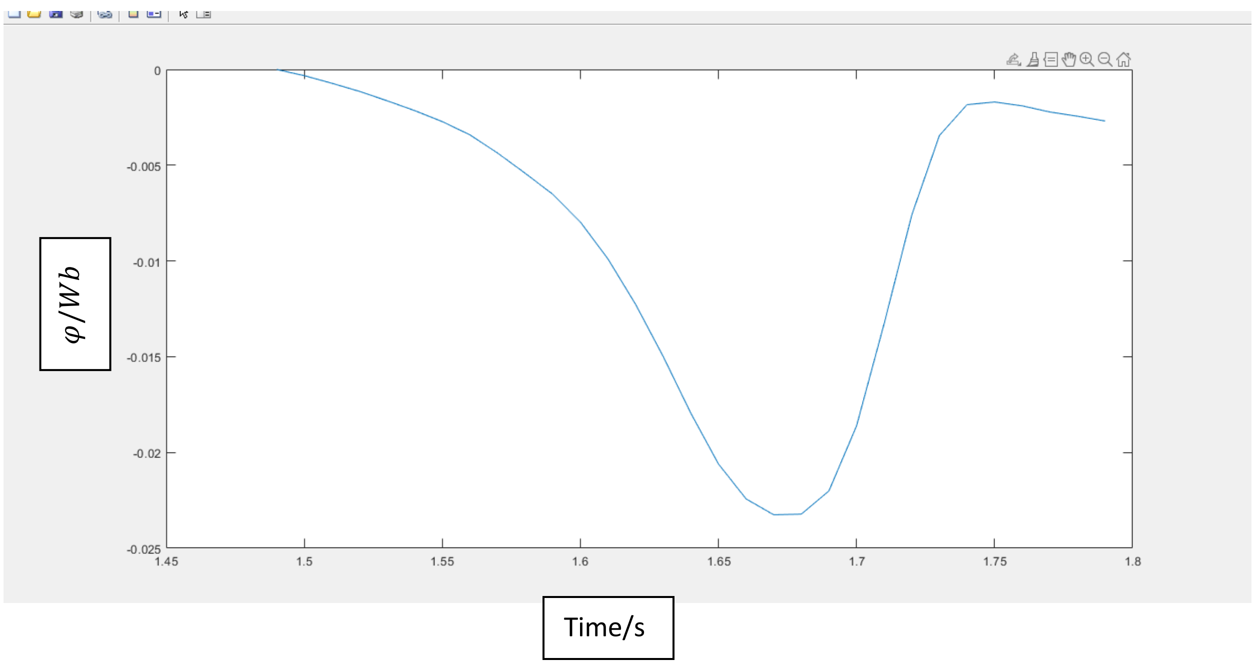
Procedure

Magnets are dropped from the top of the PVC pipe like in experiment C. However, this time, in order to obtain an increased induced flux, the number of magnets dropped was increased. The rest of the procedure remains the same.

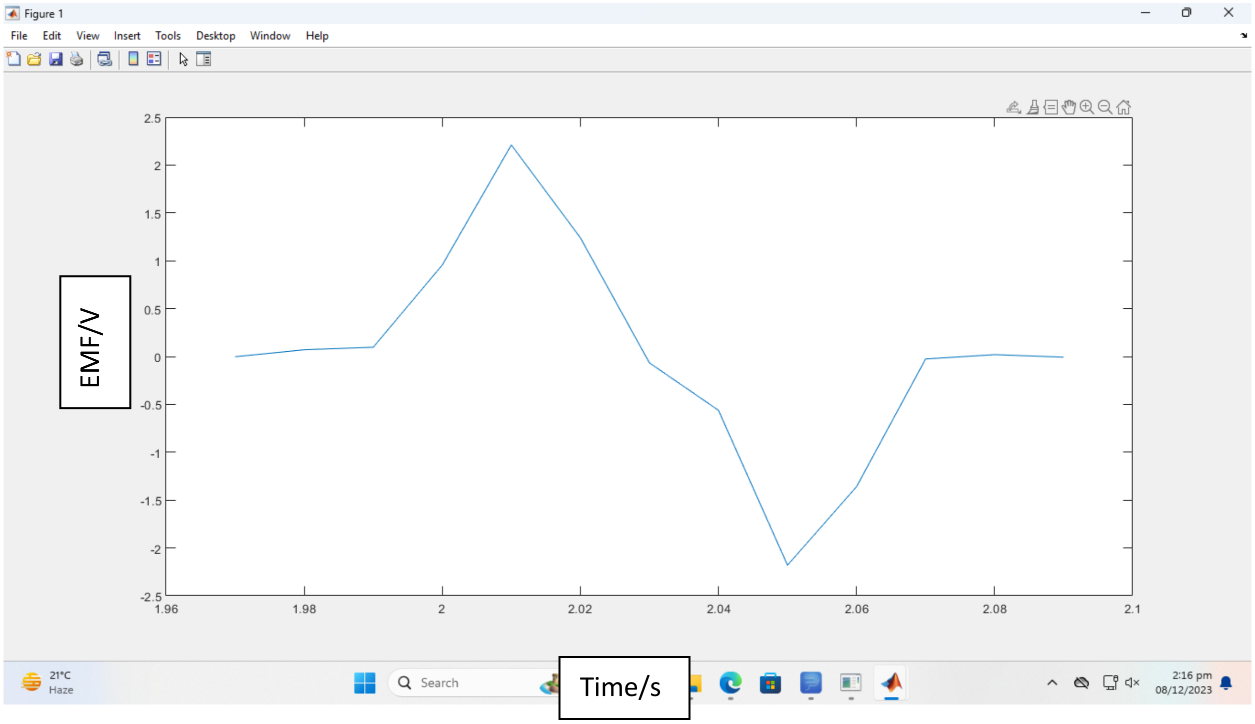
Increasing the number of magnets leads to an increase in the induced flux because the number of magnetic field lines is increased, which leads to an increase in the strength of the magnetic field.

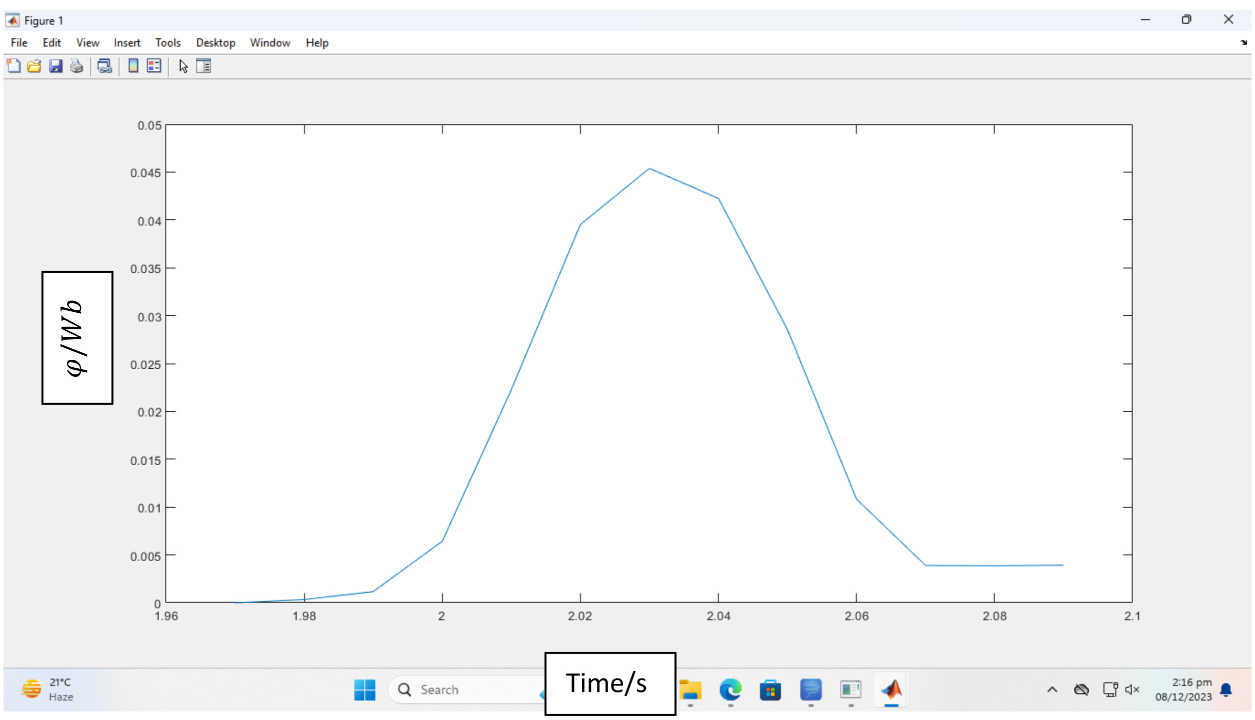
First Solenoid:





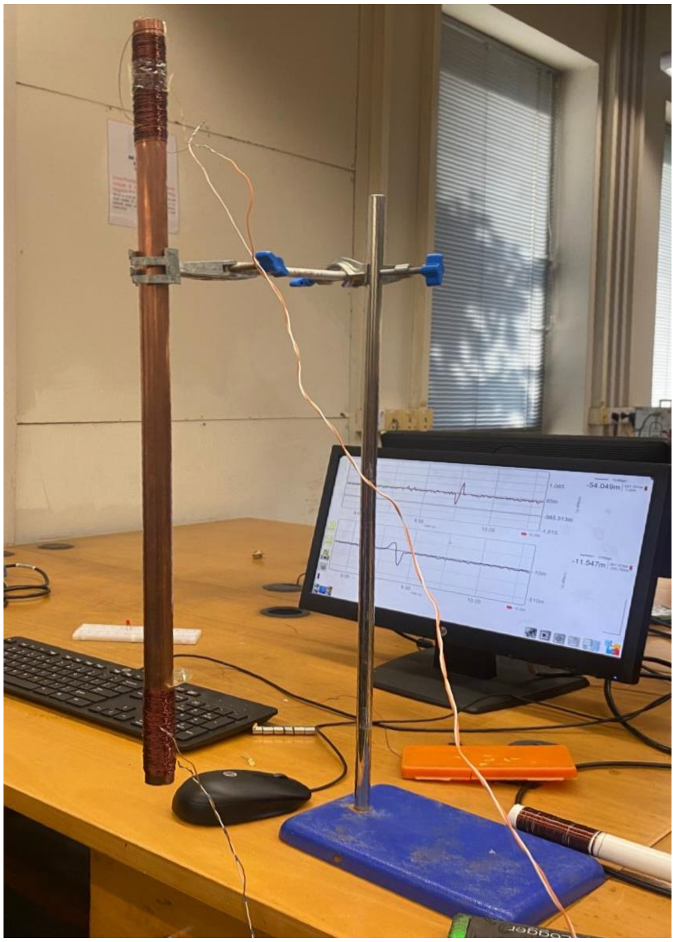
Second solenoid:





E. Electromagnetic Braking/Determining coefficient of damping k:

Experimental Setup



a) A copper pipe with copper wire wrapped around both of its ends to create two solenoids.
b) The two ends of the solenoids are soldered to the connecting wires which connect the solenoids to the PhysLogger using a connector.
c) A retort stand is used to hold the pipe vertically as the magnet is dropped inside it.

Observations

a) Damping in effect: the magnet slowed down as it fell from the top of the copper pipe to the bottom.
b) EMF was induced between the two solenoids.

Procedure

A magnet of mass = 19.7 g was dropped through a copper tube. A solenoid was wound around each end of the tube and the change in emf due to changing magnetic flus of the falling magnet was measured using Physlab logger. The net force on the magnet can be calculated by summing the downward force and the dragging force. When ‘m’ and ‘v’ are the mass and velocity of the magnet respectively, the governing equation of motion can be written as

$$m\frac{dv}{dt} = mg - kv \tag{2}$$

where ‘g’ is the acceleration due to gravity (value of g is 9.8 m s^{-2}) and ‘k’ is the damping coefficient. When ‘v_0’ is the initial velocity then the velocity will be found by integrating Eq. (2) as;

$$v(t) = \left(v_0 - \frac{mg}{k}\right)e^{-\frac{k}{m}t} + \frac{mg}{k} = \frac{dx(t)}{dt} \tag{3}$$

Then integrate the Eq. (3) to get x(t),

$$x(t) = \left(\frac{kv_0m - m^2g}{k^2}\right) - \left(\frac{kv_0m - m^2g}{k^2}\right)e^{-\left(\frac{k}{m}t\right)} + \frac{mg}{k}t \tag{4}$$

By rearranging the equation, we get

$$\frac{x}{m^2g}k^2 - \left(\frac{v_0}{mg} + \frac{t}{m}\right)k + 1 = \left(1 - \frac{v_0k}{mg}\right)e^{-\left(\frac{t}{m}\right)k} \tag{5}$$

Reference: Thottoli, A.K., Fayis, M., Mohamed, T.C., Amjad, T., Shameem, P.T. and Mishab, M., 2019. Study of magnet fall through conducting pipes using a data logger. SN Applied Sciences, 1(9), p.1050.

Damping coefficient, ‘k’ can be found by solving the above Eq. (5) by substituting the corresponding values of the distance ‘x’ (length of the pipe), mass of the magnet ‘m’, initial velocity ‘v0’, the value of ‘g’ and the time taken by the magnet to pass through the pipe ‘t’.

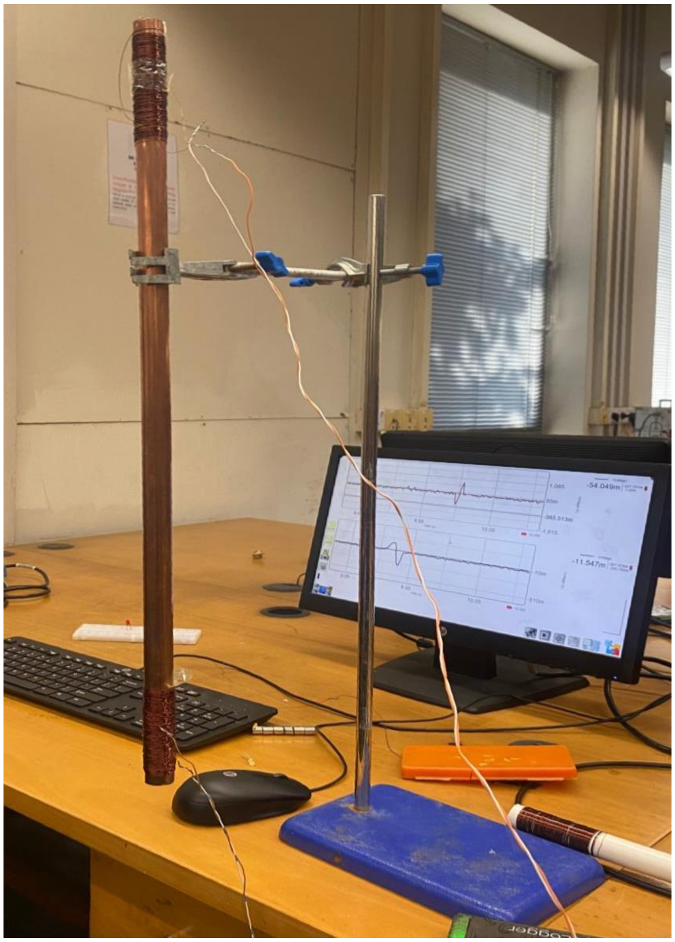
Time obtained using PhysLogger: 1.977s

Equation (5) was solved by using www.wolframalpha.com to find k value.

Damping coefficient (K) obtained: 0.689702 kg s^{-1}

F. Conductivity of Conducting Pipe

Experimental Setup



a) A copper pipe with copper wire wrapped around both of its ends to create two solenoids.
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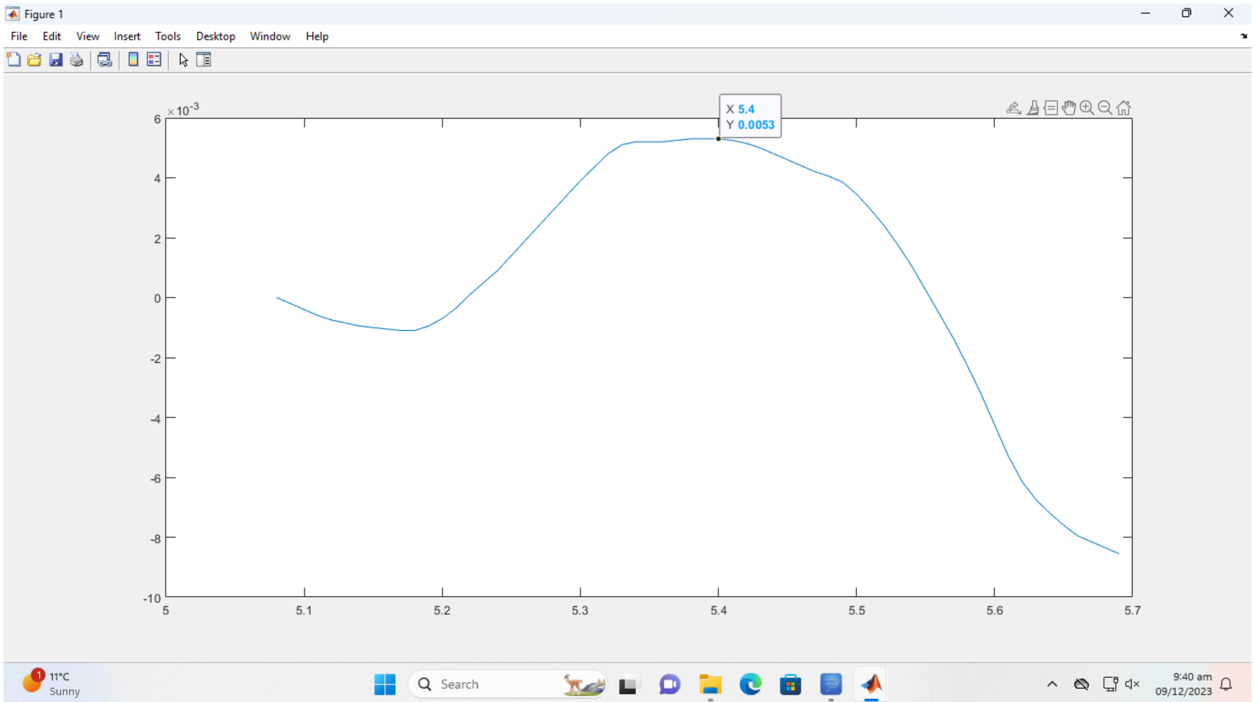
c) A retort stand is used to hold the pipe vertically as the magnet is dropped inside it.

Procedure

Magnets are dropped from the top of PVC pipe. The voltage/emf generated due to the change in magnetic flux through the solenoids is recorded by Physlogger and a live plot is generated for this emf on the Physlogger software.

This data for emf vs time for the second solenoid is imported into the Matlab software and a numerical integration function “cumtrapz” was applied on these data points to obtain the values of magnetic flux and hence, generate a corresponding graph for magnetic flux vs time.



From this graph, the maximum value of magnetic flux was noted. The conductivity was then calculated as follows:

Conductivity of copper pipe = $\frac{\sqrt{2}\pi k}{2\varphi_0}\sqrt{\frac{c^2-b^2}{ln^3\left(\frac{c}{b}\right)}}$

where ‘b’ and ‘c’ are the inner and the outer radius of the pipe. φ_0 is the maximum value of magnetic flux and is obtained numerically integrating Faraday’s law.

$\varphi_0 = 0.0053 \times 10^{-3}$

c = 1.0025×10^{-2} m

b = 7.525×10^{-3} m

So, conductivity = 0.124636×10^{5} Sm^{-1}

G. Calculation of Terminal Velocity

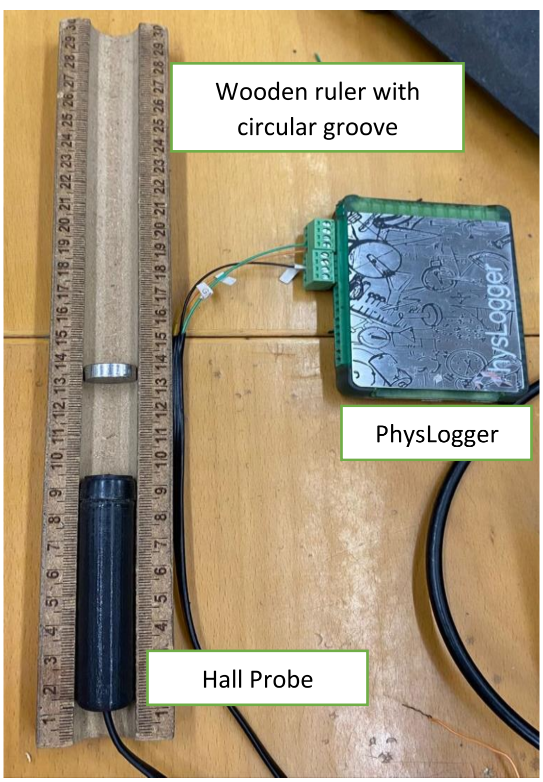
$$Terminal\ velocity = \frac{mg}{k} = 0.2802\ ms^{-1}$$

H. Evaluating the Induced Electric Current (Eddy Current)

Purpose:

The purpose of this experiment is to calculate the induced Electric Current (Eddy Current) through the evaluation of the magnetic fields of disk magnets using the hall sensor. In addition, the experiment emphasises on the reliability of Faraday's Law of Electromagnetic Induction which asserts that the EMF produced is directly proportional to the rate at which the magnetic field lines per unit area or magnetic flux 'cuts' the conducting loop. A changing magnetic field across a conductor generates an electric field. When a charge moves around a closed circuit this electric field does work on the charge.

Experimental Setup:



a) A data acquisition device (e.g. PhysLogger). The PhysLogger software is used to record and display the output voltage;

b) A Hall sensor mounted on the tip of a hall probe, used to measure magnetic fields;
c) Disk magnets;
d) A wooden ruler with a circular groove to vary the distance between the disk magnet and the flat face of the Hall probe.

Procedure

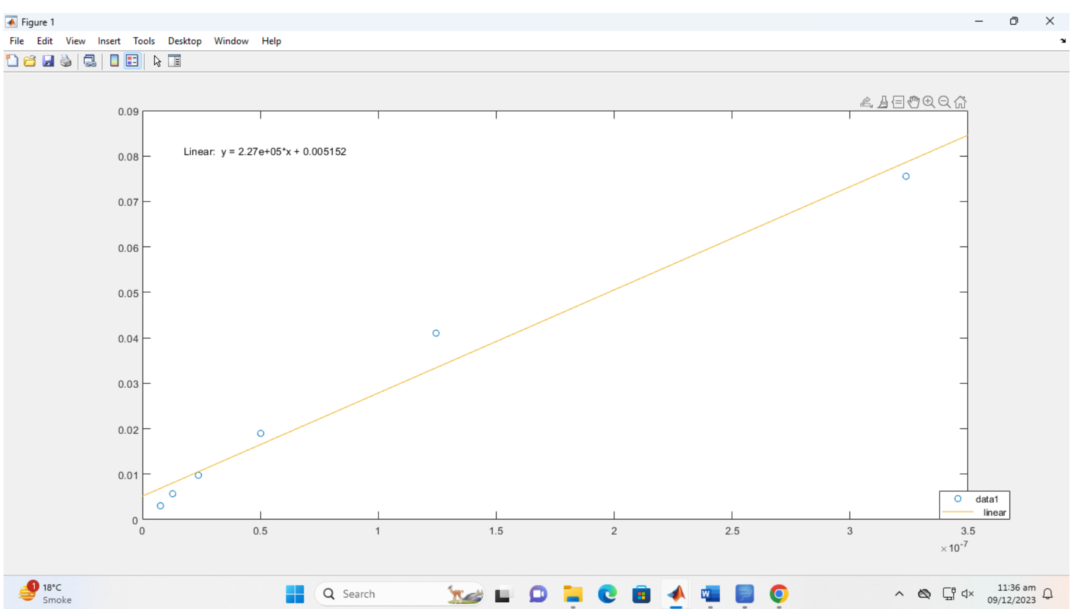
A disk magnet is placed on to the provided wooden ruler with the circular groove and the distance between the disk magnet and the flat face of the Hall probe is varied. The flat face of the probe is perpendicular to the magnetic axis of the disk magnet as illustrated in the figure provided above. The distance is varied from 0.5 to 3.0 cm in steps of 0.5 cm. The hall voltage was measured at each distance and corresponding magnetic field in Gauss was measured using the equation: $B = 320V_H - 800$. Note that $1\ G = 10^{-4}\ T$. A program in Matlab was used to measure f(x). The program prompts to enter the radius and thickness in mm. It then returns f(x).

Radius = 7.35×10^{-3} m

Thickness = 6.5×10^{-3} m

Distance x (10^{-3} m)	**Output voltage (V)**	**B measured (G)**	**B measured (T)**	**f(x) (10^{-6} T mA^{-1})**
5	4.8610	755.5200	0.0756	0.3237
10	3.7820	410.2400	0.0410	0.1245
15	3.0930	189.7600	0.0190	0.0502
20	2.8050	97.6000	0.0098	0.0237
25	2.6780	56.9600	0.0057	0.0128
30	2.5950	30.4000	0.0030	0.0076

A graph was plotted of f(x) against B.



Magnetization function is equal to the gradient of the above graph.

M = 2.27 × 10^5 A/m

The eddy current generated in the tube when the magnet reaches the bottom of the tube is calculated as follows:

$$I(z) = \frac{\mu_0 q_m a^2 v}{2R}\left[\frac{1}{(z^2 + a^2)^{3/2}} - \frac{1}{[(z^2 + d)^2 + a^2]^{3/2}}\right]$$

z = distance covered by the magnet, a = inner radius of coil, R = radius of magnet, d = thickness of the magnet, v = terminal velocity of the magnet, μ_0 = permeability of free space, $q_m = \pi R^2 \sigma_m$ (net charge of point monopoles), $\sigma_m = M$ (magnetic surface charge density)

z = 0.615 m

a = 1.0025 × 10^{-2} m

R = 7.35 × 10^{-3}

d = 6.5 × 10^{-3} m

v = $0.2802\ ms^{-1}$

$\sigma_m = 2.27 \times 10^5$ A/m

$q_m = 38.526\ Q$

I = 1.228 × 10^{-6}

Contribution Statement:

1. ***Project Deliverable Document:*** *Ayma Aamir (2027-10-0229), Areej Fatima (2027-10-0212), Hamid Ali Khan (2027-10-0156);*
2. ***Experimental Setups****: Hamid Ali Khan (2027-10-0156), Abdullah Tahir (2027-10-0219), Ayma Aamir (2027-10-0229), Areej Fatima (2027-10-0212);*
3. ***Soldering:*** *Abdullah Tahir (2027-10-0219), Hamid Ali Khan (2027-10-0156);*
4. ***Photography:*** *Areej Fatima (2027-10-0212);*
5. ***Recording Results:*** *Hamid Ali Khan (2027-10-0156), Ayma Aamir (2027-10-0229), Abdullah Tahir (2027-10-0219), Areej Fatima (2027-10-0212).*
6. ***Matlab and Graph Plotting:*** *Hamid Ali Khan (2027-10-0156).*

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