International Baccalaureate:

Extended Essay

Predictions and of the time required for a magnet drop inside a copper tube to fall for eight copper tubes with different diameters.

Research Question: How does the inner diameter of a copper tube affect the falling time of a magnet that dropped and freefalling through in it.

Physics

<u>Contents:</u>

Introduction

Electromagnetism and electromagnetic induction are topics of physics that can be observed frequently in daily life. Inductors and transformers are electrical components where electromagnetic induction can be observed. Electromagnetic induction is covered in IB Physics as an HL topic. As an IB student I wanted to set an experiment where electromotive force (emf) can be observed in a more concrete way.

The aim of this investigation is to answer the question "How does the inner diameter of a copper tube affect the falling time of a magnet that dropped and freefalling through in it?" In this experiment, falling times of 4-millimeter diameter neodymium magnet falling through copper tubes with 5-6-7-8-9-10-11-12mm inner diameter, 25cm length are measured to evaluate the relationship of emf and the distance.

This investigation aims to analyze the interaction between a moving magnetic field and a conductor.

The first step of this investigation is to evaluate the relationship of the diameters of the copper tubes and the falling times of the magnet. Then the relationship of the magnitude of emf and the diameter is going to be evaluated according to the first step.

1. Background Information:

This investigation includes Physics concept that are;

- Electromagnetic Induction
- Lenz's Law
- Eddy Current
- Magnetic Damping

A moving magnetic Field creates electromotive force (Emf). Electromotive force is defined as the work done per unit charge in moving charge across the battery terminals[1].

If motional Emf can cause a current loop in the conductor, we refer to that current as an **eddy current**. Eddy currents can produce significant drag, called **magnetic damping**, on the motion involved [2]

When a magnet falls through inside the copper tube, a moving and varying magnetic field induces eddy currents inside the tube, it initiates an interplay of electromagnetic forces.

Faraday's Law of Induction states that any change in a coil's magnetic environment will induce an emf (electromotive force) in the coil.

Lenz's Law states that the direction of the current is the opposite of the change in magnetic flux ($\Delta\phi$),[3] however, their magnitudes are same. So Emf and eddy current created by it creates a magnetic field that opposes the moment of the fall of the magnet. This decelerates the moment of magnet through the copper tube.

1.Tsokos, K. A. *Physcs for the IB Diploma*. Cambridge University Press, 2014.

2.“Eddy Current.” *LibreTexts Physics*, https://phys.libretexts.org/Courses/Georgia_State_University/GSU-TM-Introductory_Physics_II_(1112)/08%3A_Electromagnetic_Induction_AC_Circuits_and_Electrical_Technologies/8.08%3A_Eddy_Currents_and_Magnetic_Damping. Accessed 2 2024.

3. “Lenz’s law.” *GeeksforGeeks*, https://www.geeksforgeeks.org/lenzs-law/. Accessed 6 Dec. 2023.

Emf force is calculated by the formula:[4]

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

Where:

ε: represents electromotive force (EMF), induced voltage (ν)

N: represents the coil number of turns

dΦ: represents the change in magnetic flux. (ωh)

d*t:* represents change in time.

minus sign (-) represents the opposite direction of voltage generated

The slowdown in the falling speed of the magnet can be attributed to magnetic damping, which is caused by eddy currents within the copper tube creating an opposing force that counteracts with the magnet's gravitational acceleration. Gravitational force is the force make the magnet fall down and accelerates it. This phenomenon used in varying applications of technologies such as magnetic braking systems used in trains and damping mechanisms for earthquakes.

Eddy currents' strength thus the strength of the opposing force to the gravitational acceleration of the magnet increases as they get close to the surface of an excitation coil and their strength decreases with distance from the coil.[5] In this experiment copper tube Works as an excitation coil because of its electrical conductivity.

4.. "Physics." *Stack Exchange*, https://physics.stackexchange.com/questions/602044/why-physically-not-mathematically-is-the-induced-emf-of-a-rotating-coil-the-ne. Accessed 5 Feb. 2023.

5. "Eddy Current"*GeeksforGeeks*, https://www.geeksforgeeks.org/what-are-eddy-currents/. Accessed 7 Dec. 2023.

3. Exploration

Research Question: How does the inner diameter of a copper tube affect the falling time of a magnet that dropped and freefalling through in it.

Hypothesis: The results of this investigation will demonstrate a negative correlation between the inner diameter of the copper tube and the falling times of magnets. As the inner diameter of a copper tube increase the falling time of the magnet will decrease as well due to the decreasing emf.

Independent Variable: Inner diameter of a copper tube. Copper tubes with 5-6-7-8-9-10-11-12mm inner diameter, is used in this experiment.

- **Dependent Variable**: Time taken for a 4mm diameter neodymium cylindrical rod magnet to fall through the copper tube.

Control Variables:

- **Copper Tube:** The same tubes used for every trial are bought from the same supplier at the same time: Material type affects the magnitude of electromotive force produced by the magnetic flux change caused by moving magnet. Since emf creates an opposing force to the gravitational acceleration of the magnet, this force decelerates the fall movement of the magnet. This affects the falling time of the magnet. Emf with varying magnitude would change deceleration of the movement and the falling times of the magnets. The same tubes used for every trial are bought from the same supplier at the same time to prevent any variable might by it.

- **The material of every tube (copper):** is same. The material of the tube is kept constant since, changing the metal it is made of will change the electrical conductivity and the emf current inside of the tube correspondingly will change deceleration force on the movement of the magnet which will change the time required for the magnet to fall down. So, copper tubes is used in every trial.

- **Outer radius of the copper tube:** (1mm outer radius). Thickness of the tube will also, change the electrical conductivity and the Emf current inside of the tube correspondingly will change deceleration force on the movement of the magnet which will change the time required for the magnet to fall. To prevent any variable caused by it the outer radiuses of the tubes are also measured and checked if all the copper tubes with different inner diameters have the same 1mm outer radius.

- **Material and shape, and thickness of magnet:** Dropped magnets with different shapes and thicknesses will affect the rate of change of the magnetic flux. Which results in different Emf magnitude and different deceleration force applied on the falling magnet. Same magnet with 4mm diameter is used for every trial control this variable.

- **Experiment Setup:** Arduino board and electrical circuit used to detect more precise ‘falling time’ are identical.
- Room temperature: Temperature is kept constant in order to prevent expansion or contraction of the copper tubes that might create differentiations at the diameters of

the copper tubes. The room temperature is measures by thermometer(± 0.5℃) every 15 minutes.

4.Experiment Procedure and Data Collection

Cooper tube is used in this experiment since;

- Cooper is a diamagnetic and conductive. The conductivity helps with the induced current to have observable properties.
- Cooper is moderately cheap in comparison with the other diamagnetic materials, so it makes is easier and more affordable to try with different diameters and lengths of tube.

4.1 Material List:

- Copper Tube (1mm outer radius, 5-6-7-8-9-1011-12mm inner diameter, 25cm length)
- Neodymium Cylindrical Rod Magnet (4mm diameter)
- Aluminum foil
- Power cord (10 units)
- Arduino Uno
- Arduino bread board
- Electrical tape
- 4 Copper wires (14cm long)
- 4 Crocodile cables
- Computer
- Carton
- Resistor 1kΩ (kiloohm)
- Thermometer (± 0.5℃)

Diagram1: Experiment setup and name of materials used

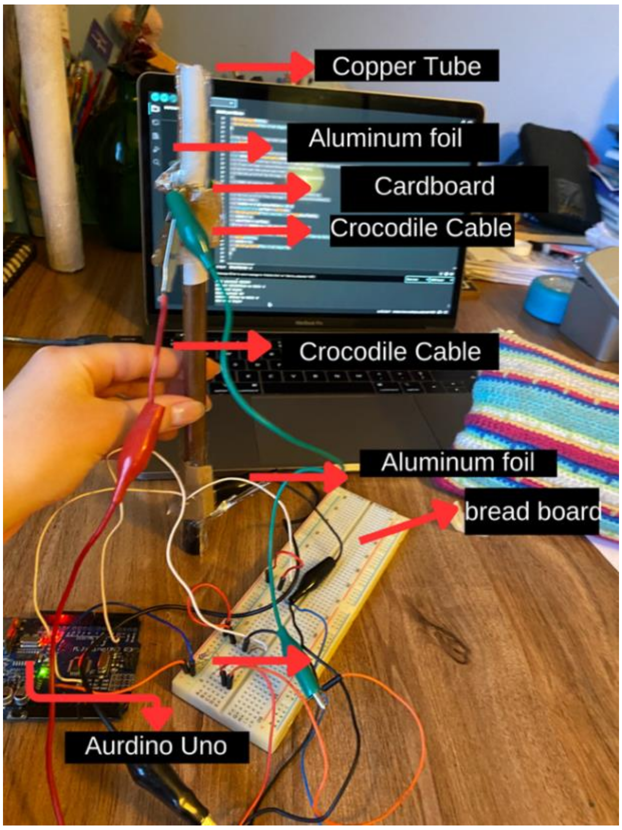
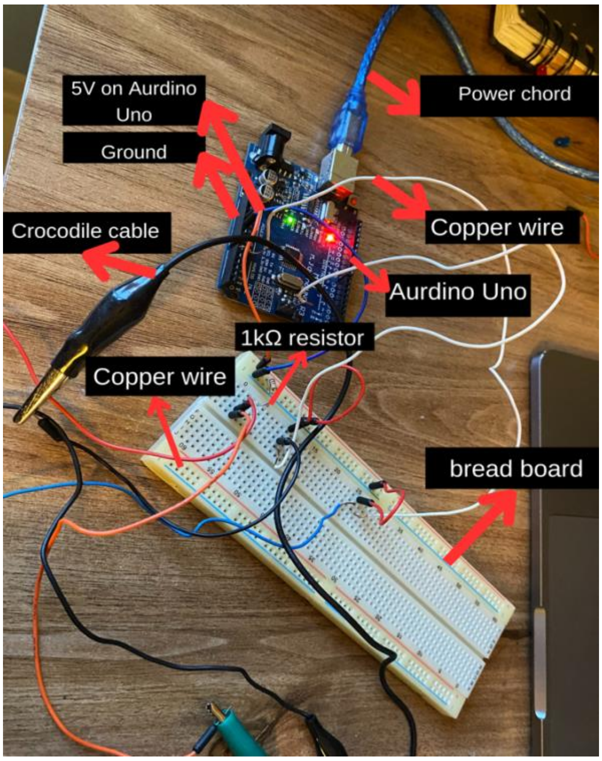


Diagram2: Setup of electrical circuit used in experiment setup and names of materials.



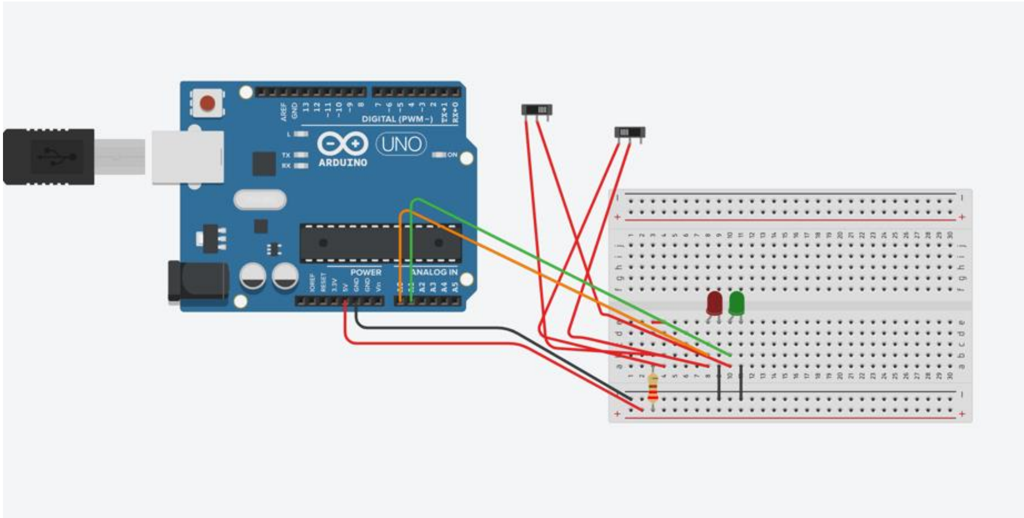


Diagram3: Thinkercad model of the electrical circuit.

4.2 Methodology:

Preparing the copper tubes:

1. Cover the ends of all copper tubes with electrical tape for 7 ±0.05 cm each end.
2. Cover the 2 centimeters under the electrical tape with cardboard so that the magnet does not stick to the iron clip of the crocodile cable while falling through the copper tube.
3. Fold aluminum foil to make 5±0.05 cm length 0,5 ±0.05 width rectangle.
4. Tape 2 rectangle aluminum foils over the electric tapes and fold the 1 cm long sections to fit over the hole of the copper tube. Make sure there is a gap as the size of the 4mm magnet between the folded parts of the aluminum foils.
5. Repeat the process for both upper and bottoms parts of the copper tube.

Preparing the circuit that detects the falling time;

6. Download "Arduino IDE" program to write the code to detect the falling times of the magnets by milliseconds by Arduino Uno board.
7. Write the code to detect the falling times of the magnets by milliseconds by Arduino Uno board:

```
void setup() {
```

```
  // initialize serial communication at 9600 bits per second:
  Serial.begin(9600);  }
// the loop routine runs over and over again forever:
void loop() {
  // UP: A0 analog input
  // read the input on analog pin 0:
  int sensorValue = analogRead(A0);
  // Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V):
  // float voltage = sensorValue * (5.0 / 1023.0);
  // print out the value you read:
 Serial.println("Up Voltage: "+ String(sensorValue));
  // DOWN: A1 analog input
  int sensorValueDown = analogRead(A1);
  // float voltageDown = sensorValueDown * 5.0 / 1023.0;
  Serial.println("Down Voltage "+ String(sensorValue));   }
```

8. Connect the 5V on Arduino board with the "+" row on the Arduino bread board with a copper wire.
9. Connect the Ground on Arduino board with the "-" row on the Arduino bread board with a copper wire
10. Connect 1 kΩ resistor into "a3" and "+3" holes on the Arduino bread board.
11. Attach one clip of crocodile cable to a cooper wire that logs into "b4" and the other clip to one rectangle aluminum foil at the bottom of the copper tube.
12. Attach one clip another crocodile cable to a cooper wire that logs into "b10" and one clip to the other rectangle aluminum foil at the bottom of the copper tube.
13. Attach one clip of the third crocodile cable to a cooper wire that logs into "c4" and one clip to the other rectangle aluminum foil on the top of the copper tube.
14. Attach one clip of the fourth crocodile cable to a cooper wire that logs into "c10" and one clip to the other rectangle aluminum foil on the top of the copper tube.
15. Log one end of a copper wire into "-10" and the other end into "a10"

16. Lastly connect the “A0” on the Arduino Uno with “b15” by a copper wire.

Detecting the falling time:

17. Connect the Arduino Uno board to the computer with a power cord.
18. Make sure the magnets are touching the aluminum foils on the top of the copper tube before you drop it.
19. Drop the magnet from the top of the copper tube.
20. Check the value written next to “time to fall”. The falling time of the magnet is measured as millisecond.
21. Detect the falling time with 5 different trials.
22. Then repeat the process for 5-6-7-8-9-10-11-12 mm inner diameter copper tubes.

4.3 How Does the Experiment Setup Works?

In this experiment setup benefited from the conductivity of the magnet. When the magnet is right on top of the copper tube it works as a conductive bridge between aluminum foils, so current can pass through them. Arduino Uno draw 5V from the computer by a power cord. This 5V is conducted to bread board and conducted to 4 crocodile clips by the right adjustments with copper wires and resistor on the bread bord. Those crocodile clips attach to the aluminum foils that are taped to the upper part of the copper tube. so, 5v passes through the aluminum foils when the magnet is right on top of the copper tube. This forms the upper part of the electrical circuit. The Arduino code written in Arduino IDE Program reads when the current is passing through the upper part of the circuit. When the magnet is dropped the code cannot read any current passing through the circuit since, there is not a conductive bridge between aluminum foils. The code starts the falling time when it reads any current. When the magnet hits the bottom of the copper tube, it connects the bottom two aluminum foils. So, current can be read from the bottom part of the circuit. This is when the Arduino code stops the falling time.

The code calculates the falling time by subtracting the millisecond when it detected the current again from when it detects the first current.

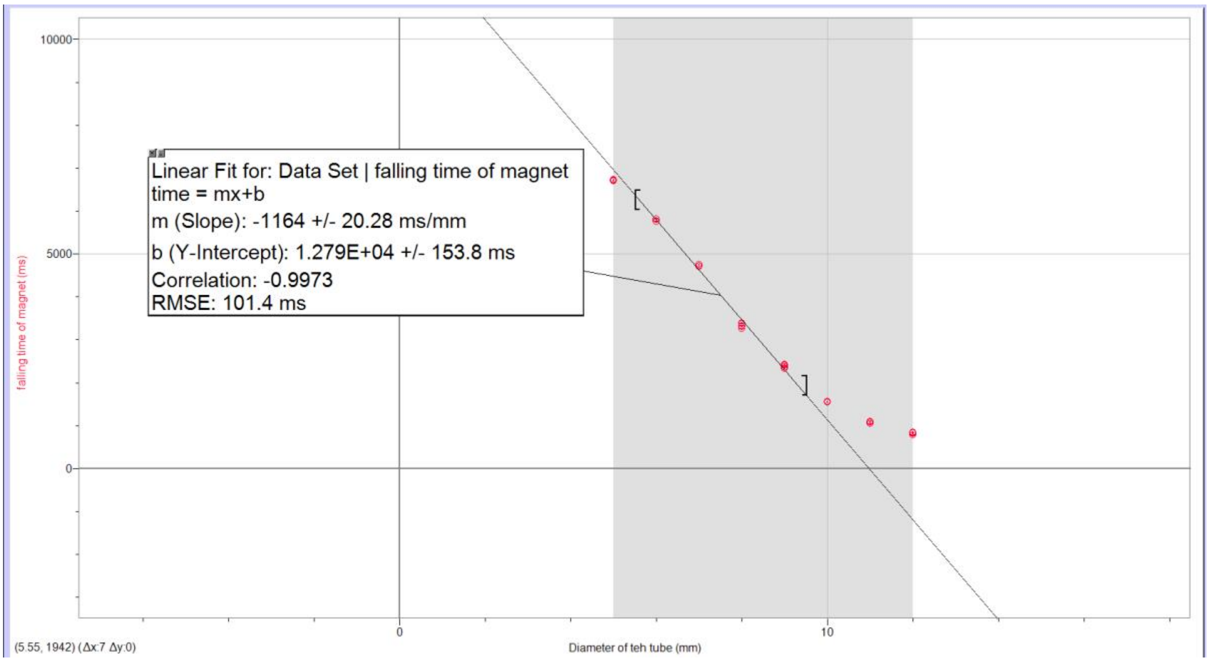
5. Data Collection and Analyses

5.1 Empirical Data:

Inner Diameters of the Copper Tubes ($\pm 0.5mm$) $-$millimeter	**Trials**	**Falling Times of the Magnets milliseconds ($\pm 0.001s$)**
5	1	6719
	2	6698
	3	6729
	4	6718
	5	6697
6	1	5813
	2	5760
	3	5810
	4	5816
	5	5750
7	1	4717
	2	4755
	3	4720
	4	4716
	5	4714
8	1	3390
	2	3263
	3	3318
	4	3310
	5	3369
9	1	1920
	2	1930
	3	1927
	4	1920
	5	1933
10	1	1556
	2	1560
	3	1550
	4	1552
	5	1564

11	1	1046
	2	1076
	3	1048
	4	1078
	5	1090
12	1	780
	2	842
	3	823
	4	821
	5	830

Table 1: The time takes for the magnets to freefall through copper tubes with different inner diameter of the copper tubes.



Graph1: The change in the falling time of the magnet according to the inner diameter of the copper tube it is falling through it.

The graph shows the change of the time taken for the magnet to fall down through the copper tube (millisecond), according to the inner diameter of the copper tube (millimeter). Linear relationship is obtained from this data set, and with correlation: -0.9973 quite close to the maximum correlation value -1.000. As the accuracy of the data set is increased by minimizing the systematic and random errors the correlation value will get closer to -1.000 even more. . As the hypothesis of this investigation claimed the correlation between the inner diameter of the copper tube and the falling time of the magnet is negatively correlated.

Linear fit line is formed by the function $\gamma = mx + c$. Slope (m) of the graph is -1164 $\pm 20.28 \frac{ms}{mm}$. Y- intercept which is 'b' value in this equation is $1.2794\text{E} + 0.4 \pm 153.8$ ms. This linear graph does not intersects with origin$(0,0)$ since the inner diameter and the falling time is negatively proportional.

This means the more $x-$ $value$ ($inner\ diameter\ of\ the\ tube$) gets closer to 0 the more y- $value$ ($falling\ time\ of\ the\ magneet$) increases and gets further from the origin.

The mean of the times takes for the magnet to go through the 25.00 cm length copper tube from every 5 trials is calculated to analyze the data collected better.

5.2 Analyzed Data:

Inner Diameters of the Copper Tubes ($\pm 0.5mm$) $-$millimeter	**Mean Falling Time (second) (5sf)**	**Standard Deviation (5sf)**	**Standard Error of Mean Time (5sf)**
5	6.7122 ± 0.016	≈ 0.0148	$\approx$ 0.0661
6	5.7898 ± 0.033	≈ 0.0320	≈ 0.0143
7	4.7238 ± 0.021	≈ 0.0172	≈ 0.0077
8	3.3300 ± 0.059	≈ 0.0504	≈ 0.0225
9	1.9240 ± 0.006	≈ 0.0059	≈ 0.0026
10	1.5524 ± 0.022	≈ 0.0057	≈ 0.0026
11	1.0676 ± 0.031	≈ 0.0335	≈ 0.0154
12	0.8192 ± 0.031	$\approx$ 0.0218	≈ 0.0097

Table 2: Processed Data of Mean Falling time, Standard Deviation of the data points and Standard Error of mean.

- **Calculating Mean:**

Mean of Time = $\frac{Trial1+Trial2+Trial3+Trial4+Trial5+Trial6+Trial7+Trial8}{8}$

- **Calculating the Uncertainty of Mean of Time:**

$$\text{Uncertainty of Mean of Time} = \frac{\boldsymbol{Max\ time - Min\ time}}{\mathbf{2}}$$

- **Standard deviation:** Standard deviation is calculated by using the formula.

$$\sigma = \frac{\sqrt{\Sigma(\chi-\mu)^2}}{\mathrm{N}}$$

σ: Standard Deviation

χ : Represents a value in the data set

μ: the mean of the data set

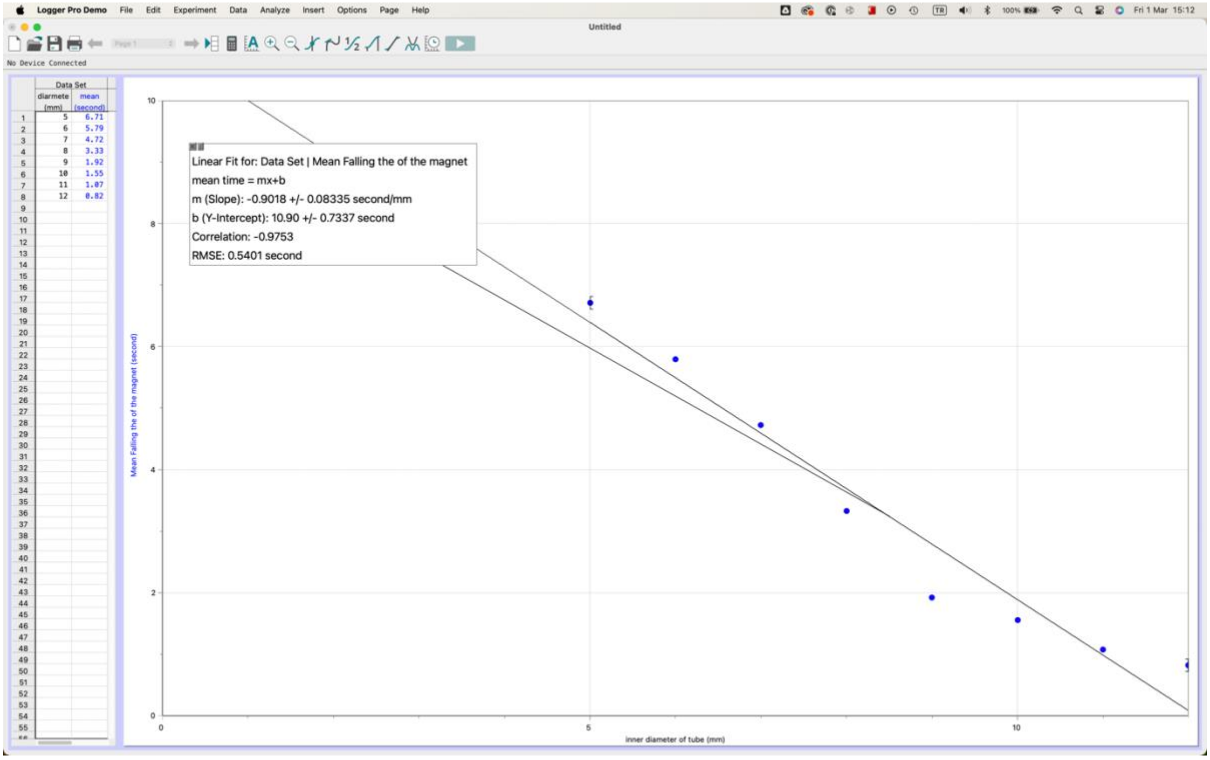
N : Number of data points in the data set

Standard errors of the mean (SEM): Standard errors of the means are calculated by dividing the standard deviation (σ) by the square root of the number of data points.[5]

$$\text{SEM} = \frac{\sqrt{\sigma}}{\mathrm{N}}$$

σ: Standard Deviation

N : Number of data points in the data set



Graph 2: Change Arithmetic average of falling times of the magnet according to the inner diameter of the copper tube.

Arithmetic average of falling times of the magnet of 8 trials is calculated for each inner diameter(5,6,7,8,9,10,11,12mm). Data set forms a linear graph with correlation -0.9753. The As the accuracy of the data set is increased by minimizing the systematic and random errors the correlation value will get closer to -1.000. As the hypothesis of this investigation claimed the correlation between the inner diameter of the copper tube and the falling time of the magnet is negatively correlated.

Slope(m) of the graph is 0.9018 ± 0.0833 milliseconds. Y- intercept which is 'b' value in this equation is 10.9 ± 0.7337 second.

This linear graph does not intersects with origin$(0,0)$ since the inner diameter and the falling time is negatively proportional.

This means the more $x - \ value\ (\ inner\ diameter\ of\ the\ tube)$ gets closer to 0 the more

y- $value\ (falling\ time\ of\ the\ magneet)$ increases and gets further from the origin.

Evaluation

Strengths

- **Controlled Variables:** I controlled varibales such as the material of every tube, outer radius of the copper tube, thickness of the tube, shape, and thickness of magnet, arduino board and electrical circuit used in order to not create a second independent variable. This ensures any changes observed in falling time of the copper tube is caused by the change in the inner diameter of the copper tube.
- **Repetitions:** Observing five trials for each different inner diameter. Repeating measurements decreases random error.
- **Standardized Setup:** Standardizing the setup of the experiment across all trials and ensuring consistency in factors such as drop height, magnet placement, and environmental conditions would reduce variability and enhance the reliability of the results.
- **Experiment Setup:** The electrical circuit and Aurdino Uno board I used to detect the falling time helped me to measure the falling time with 10 significant figures for millisecond to detect the change in falling time more precisely. I made my measurements in millisecond since even the longest falling time of the magnet is shorter than 10 seconds. Since, I was measuring small minutes I used millisecond to detect even the smallest changes in the falling time.

Weaknesses:

Lack of Calibration: Calibration of the Aurdino board and setup have not been done.Calibration of the AurdinoUno Board would effect the accuracy of the falling time measurements.

Magnetic Force: A piece of cardboard is used to prevent the magnet sticking to the iron head of the crocodile cable which will prevent the magnet to fall inside from the tube. The magnet can fall down becausee of the cardboard however, it is not certain that the magnetic force between the iron and magnet is zero. This may result in systematic error, observed falling times are might be higher than thee actual results because of the magnetic force between iron and magnet.

Limitations:

- **Electrical Circuit**: The use of electrical components such as Aurdino Uno Board, conductive cables in a experiment setup might cause potential sources of error, such as electromagnetic interference or inaccurate timing due to the precision of the Arduino Uno board.
- **External Factors:** External factors such as air resistance or external force apllied to the magnet during dropping couls affect the falling time of the magnet and may not be fully controlled in this experiment.

Improvements:

Calibration: Calibrating the electrical circuit materilas for the timing system by using a known falling object with a precisely measured falling time, would ensure the accuracy of the measurements obtained from the Arduino Uno board and reduce the systemical error

Error Analysis: Conducting a thorough analysis of potential sources of error, such as promles that can be caused by electrical interference in the experiment setup would improve the accuracy of the experiment.

Dropping the Magnet: An extra esperiment setup created eliminate the external force on magent while dropping might increase the accuracy by reducing systematic error**.**

Further Investigation:

Material Composition: For further investigation, effect of the material of the tube on the falling time of the magnet might be investigated. Using different materials other than copper for the tube, such as aluminum, cardboard, or plastic, could provide comparative data about how material properties influence the experiment's outcomes.

Temperature Dependency: Temperature could be the independent variable for a further investigation. Investigating the effect of temperature on the falling time of the magnet could reveal any temperature-dependent effects on magnetic flux index, the falling time of magnet within the copper tube.

Magnet Configuration: Further experiments can be done with different magnet configurations, such as magnets with different size or strength. This investigation could provide data about how magnet characteristics impact the falling behavior and time taken for the fall.

Conclusion

A magnet falling through a copper tube creates a change in magnetic flux. This creates Emf and induces eddy currents on the tube walls. Direction of Emf opposes with the gravitational acceleration of the magnet. So, Emf decelerates the magnet and elongates the falling time according to the time required for the magnet fall with zero opposing forces to gravitational force. According to the data obtained from this experience eddy current concentrate near the surface of the copper tube and the magnitude of the braking force (emf) applied on the magnet decreases as the distance between the magnet and the walls of the copper tube increases. From these observations and the graph formed from the data obtain it shows that the braking force on the magnet and the eddy current on the tube walls negatively proportional. As the inner diameter of the copper tube decreases magnitude of emf increases thus, the braking force effect increases. This braking force decelerates the movement of the magnet and elongates the falling time of the magnet. The hypothesis of this investigation claimed the correlation between the inner diameter of the copper tube and the falling time of the magnet is negatively correlated. The data obtained and analyses made from these data approved the hypothesis of this investigation.

Word Count: 3533

Citations:

1. Tsokos, K. A. *Physcs for the IB Diploma*. Cambridge University Press, 2014.
2. "Eddy Current." *LibreTexts Physics*, https://phys.libretexts.org/Courses/Georgia_State_University/GSU-TM-Introductory_Physics_II_(1112)/08%3A_Electromagnetic_Induction_AC_Circuits_and_Electrical_Technologies/8.08%3A_Eddy_Currents_and_Magnetic_Damping. Accessed 2 2024.
3. "Lenz's law." *GeeksforGeeks*, https://www.geeksforgeeks.org/lenzs-law/. Accessed 6 Dec. 2023.

4.. "Physics." *Stack Exchange*, https://physics.stackexchange.com/questions/602044/why-physically-not-mathematically-is-the-induced-emf-of-a-rotating-coil-the-ne. Accessed 5 Feb. 2023.

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