IBDP Physics HL Extended Essay

Title:

Investigating the effect of the diameter of the hole inside a copper pipe on the time of a neodymium magnet to pass through it.

Research Question:

How does the diameter of the hole inside of a copper pipe (3.5, 5.0, 6.5, 8.0 and 9.5 cm) with 30cm height affect the time for a neodymium magnet with a diameter of 3.0 cm and height of 1.5 cm to pass through it?

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I. Introduction

I came across this experiment in a video last year when I was surfing the internet. In the video, the experimenter dropped a magnet into a copper pipe and the magnet reached the ground much slower that it would under normal circumstances. It immediately caught my eye. It was a simple experiment yet it had a very complex theoretical background. While I was searching for a subject for my Physics Extended Essay, I initially had not thought of this experiment. However, when I saw a post on a site that they used this experiment for their Extended Essay, I decided this was the best option. I also considered the fact that my father was an electrical engineer who had knowledge regarding this experiment and could provide me the required materials if my school did not have them.

II. Background information

II. A. Historical Background

The word ''eddy'' means ''circular current''.[1] Eddy currents were first observed in 1823 by François Arago (Figure 1.3) , a mathematician, scientist, astronomer and a politician. He was the first person who experienced rotating magnetism which allowed him to understand that most conductive materials could be magnetized. Heinrich Lenz (Figure 1.1) proposed the ''Lenz's Law'' 10 years later. However, eddy currents were only formally proposed in 1855 by French scientist Léon Foucault (Figure 1.2). Eddy Currents are sometimes called ''Foucault Currents''. Foucault conducted several tests and deduced that when the rim of a copper disk is put in between poles of a magnet, the required force to spin it increases. This resulted in heat being produced due to eddy currents. [2]

Figure 1.1

Figure 1.2

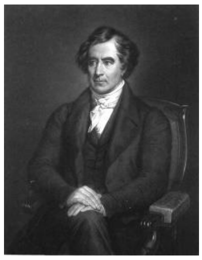


Figure 1.3

II. B. Theoretical Background

In order to understand eddy currents, one must understand Faraday's Law of Induction and Lenz's Law. The observations originating from these laws form the basis for understanding eddy currents. Faraday's Law of Induction (Figure 2.1) is named after, Michael Faraday, and English scientist who lived in 19th Century and proposed the law.[3] According to Faraday's Law, any change in the magnetic environment will result in a voltage (emf) being induced in the coil. Voltage will be generated regardless of how the change is produced. This change in the magnetic environment can be initiated in several ways such as changing the magnetic field strength or moving a magnet away or towards the coil. [4]

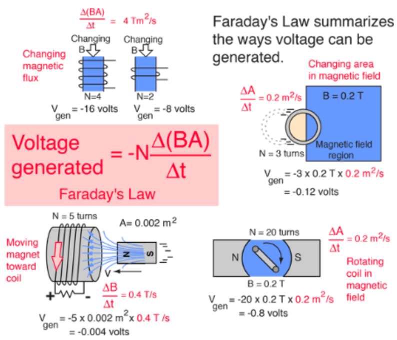


Figure 2.1

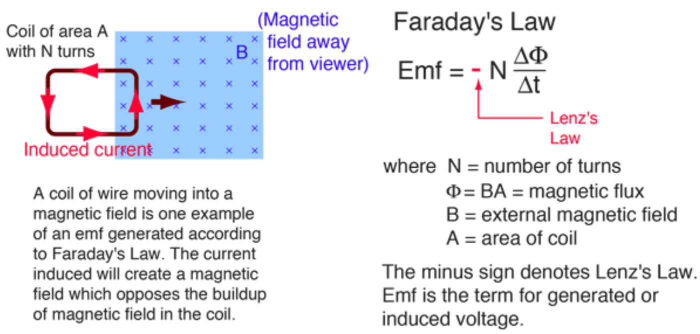


Figure 2.2

Lenz's Law (Figure 2.2) was proposed by Heinrich Lenz which could be seen as an addition to Faraday's Law. Lenz's Law allows the prediction of directed emf induced by the changing magnetic field. The directed emf would generate a current to flow in the conductor which would create an extra magnetic field which opposes the change in the original magnetic field.[5] These currents which form as a reaction to the original magnetic field are known as eddy currents. These currents flow through conductors like eddies in a stream and are perpendicular to the magnetic field. (Figure 2.3). Eddy currents also lead to energy loss in the conductor.[6]

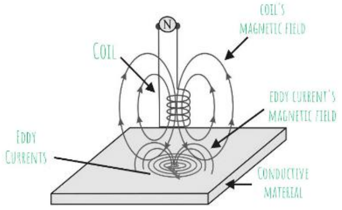


Figure 2.3

II. C. Real World Applications of Eddy Currents

Eddy currents have many applications in the real world which some make up crucial elements of certain systems. The following are the examples of real-world use of eddy currents.

II. C. i. Transformers

Eddy currents often result in power loss in transformers. Transformers (Figure 3.1) are constructed with thin strips of metal rather than a one-piece machine. Glue is used to insulate these thin strips which contain the eddy currents into the strips which in turn reduces power loss. [7]

II. C. ii. Breaking mechanism of trains

Trains have metal wheels which run on metallic tracks (Figure 3.2). When brakes are initiated, the metal wheels of the train are ixposed to a magnetic field which induces eddy currents in the wheels. The wheels and the magnetic field interact and slow the train down. [8]

II. C. iii Safe testing

Eddy currents have a use of flaw identification in large machines or structures such as aeroplanes (Figure 3.3). A change in the number of eddy currents indicates a change of magnetic field in a specific location. This change of magnetic field is observed as an irregularity on the metallic surface of the machine or structure. [8]

II. C. iii Speed indicators in vehicles

Cars, planes, motorcycles or any other vehicle used for transportation have ‘speedometers’ (Figure 3.4) which shows the speed of the vehicle in a particular time. In response to a change in speed, the magnet rotates. Eddy currents form inside the drum where the drum moves in the direction of the magnet which results in the indicator displaying the current speed. [8]

Figure 3.1

Figure 3.2

Figure 3.3

Figure 3.4

III. Designing the experiment

When the neodymium magnet is dropped, it creates a change of magnetic field pushes electrons around circular eddy currents. Since it is known that eddy currents have their own magnetic field which opposes the fall of the magnet.[9] In figure 4.1, the south pole of the magnet which faces upwards is pulled by the upper eddy current which has its north pole facing downwards.

The lower eddy current which has its northern pole faced up pushes the magnet which has its northern pole faced downwards. This process slows down the fall of the magnet trough the copper pipe by stabilizing its velocity instead being accelerated by gravity if it were to fall through a non-metal pipe. [10]

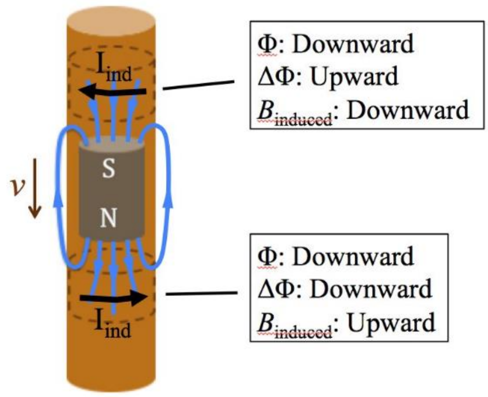


Figure 4.1

The primary goal of this experiment will be to investigate how eddy currents which from when a neodymium magnet falls through a copper pipe slow down the magnet despite gravitational acceleration. Five copper pipes will be used. Each pipe will have the height of 30 cm and the total diameter of the pipes will remain constant while the diameter of the holes inside of the pipes will increase as the trials go on. For all trials, the same neodymium magnet will be used. This magnet is of a cylindrical shape and has a diameter of 3 cm and a height of 1.5 cm. A digital stopwatch will be used to record the time taken for the magnet to reach the ground. Since the magnet makes a relatively loud sound when it hits a flat and hard surface, the observer will suspend the stopwatch when they hear the sound. For every diameter value, the experiment will be repeated five times to observe the effect and minimize uncertainty.

III. A. Variables

Type of variable	Variable	Method of measuring
Independent	The diameter of the hole inside the copper pipe (3.5cm, 5cm, 6.5cm, 8cm, 9.5cm).	The diameters were measured by a ruler.
Dependent	The time taken for the neodymium magnet to reach the ground.	A stopwatch will be used to measure the time.

Controlled variable	Method of control	Reason for control
Height of copper pipes	Measured by a ruler, all copper pipes have a height of 30 cm.	Time required for the magnet to reach the ground would be affected if the copper pipes had different heights.
Volume and type of neodymium magnet	The same cylindrical magnet is used in all trials with 3cm diameter and 1.5cm height	Since the distance between the magnet and the copper surface is changed by changing the diameter of the hole inside the copper pipe, the volume and type of the magnet must be constant to observe the effect of changing the diameter of the hole.
The total diameter of the copper pipes.	All copper pipes have the same total diameter (10cm). The diameter of the holes inside	While this does not theoretically effect the time to reach the ground, it is decided to keep it controlled for the sake of being precise

III. B. Equipment

- A cylindrical neodymium magnet with a diameter of 3 cm and height of 1.5 cm
- Five copper pipes with uniform height (30cm) and total diameter (10cm) but with holes inside them with different diameters (3.5cm, 5.0cm, 6.5cm, 8.0cm, 9.5cm).
- A Stopwatch
- Ruler longer than 30cm.
- Gloves

- Notebook
- Pencil

III. C. Procedure

1- Put on the gloves. The magnet or the copper pipes are not toxic but can leave a heavy smell if the experimenter touches it without gloves.

2- Prepare the stopwatch. It must be made sure that the experimenter holds the stopwatch in one of their hands. This is done to eliminate or at least minimize the human uncertainty of human reaction time which is 0.11 seconds.

3- Put the first copper pipe on a flat hard surface and make sure that it stands still.

4- Grab the magnet with your free hand and hold it inside the copper pipe.

5- Make sure that the neodymium magnet is fully inside the copper pipe and that its top does not peak outside and is in the same level as the top of the pipe.

6- Set off the stopwatch and release the magnet at the same instant.

7- During the fall, only look at the stopwatch. Since the experiment takes place on a hard and flat surface, the magnet will make a loud sound which the experimenter will be able to hear.

8- Immediately turn off the stopwatch once the magnet reaches the ground and makes the sound.

9- Note the recorded time on the notebook to the nearest digit.

Below, Figure 5.1 presents the experiment set up with labels.

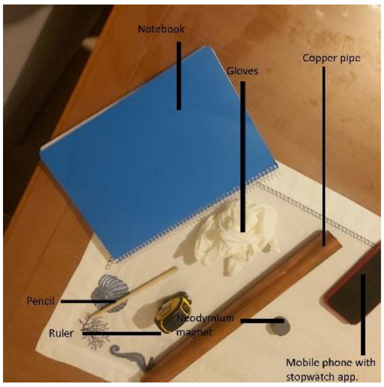


Figure 5.1

III. D. Hypothesis

As the diameter of the hole inside the copper pipe increases, the magnet will reach the ground in a shorter time. This is because as established in the 'Theoretical background' section, the increase of distance between the neodymium magnet and the surface of the copper pipe will result in the decease the in the effect of magnetic friction, therefore decreasing the impact of the responding magnetic field that Lenz's Law states.

III. E. Safety, ethical and environmental concerns

Safety: It must be considered that the copper pipes used in the experiment are quite large and heavy which can cause moderate injuries if used without caution. Additionally, it would be wise keep the pipes away from small children and animals.

Ethics and environment: It would be quite unethical to dump the pipes and the magnet to the environment especially near water sources since these are potentially contaminating metals. Most optimal way to deal with this is to provide the pipes to a factory or a construction area where it could be useful.

IV. Data and analysis

IV. A. Raw Data

Below, Table 1 presents the raw data collected from the experiment. For each value, the

Diameter of the hole inside the copper pipe (± 0.05 cm)	Trial	Time taken to reach the ground (± 0.001 s)
Group 1 (3.5cm)	1	1.125
	2	0.896
	3	0.789
	4	1.012
	5	1.198
Group 2 (5.0cm)	1	0.887
	2	0.904
	3	0.696
	4	0.771
	5	0.765
Group 3 (6.5cm)	1	0.715
	2	0.541
	3	0.852
	4	0.624
	5	0.722
Group 4 (8.0cm)	1	0.623
	2	0.501
	3	0.446
	4	0.505
	5	0.761
Group 5 (9.5cm)	1	0.323
	2	0.297
	3	0.453
	4	0.334
	5	0.488

Table 1: Raw data collected for every diameter group (3.5, 5.0, 6.5, 8.0 and 9.5 cm)

IV. B. Processed data

To observe the relationship and recognize errors, the mean of group is taken. Below, Table 2 presents the means of all groups as well as their standard error.

Diameter group	Mean time taken to reach the ground (s)	Standard error (s)	Percentage error
Group 1 (3.5cm)	1.004	± 0.205	20.4%
Group 2 (5.0cm)	0.805	±0.104	12.9%
Group 3 (6.5cm)	0.691	±0.156	22.6%
Group 4 (8.0cm)	0.567	±0.158	27.9%
Group 5 (9.5cm)	0.379	±0.096	25.3%

Table 2: Mean and standard error for each group.

Example calculations for mean, standard error and percentage error

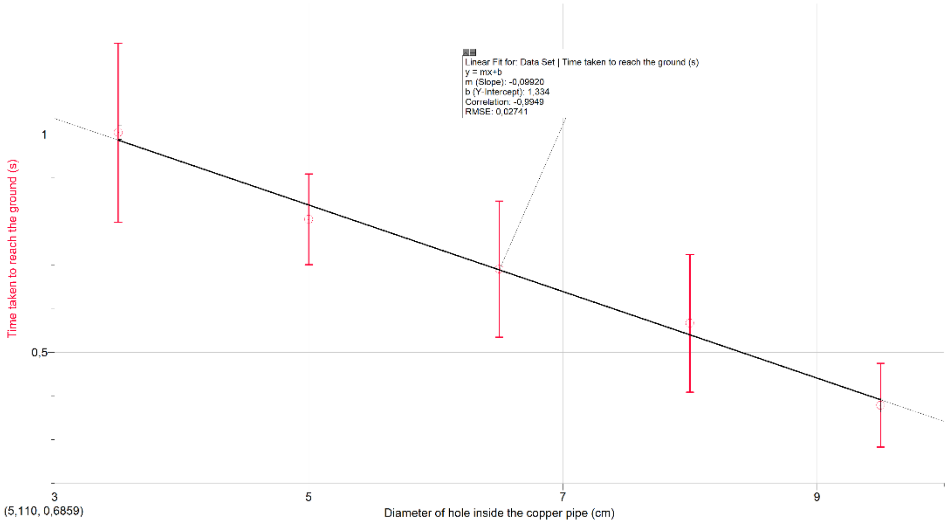
Calculation of the mean for Group 1: $\frac{1.125 + 0.896 + 0.789 + 1.012 + 1.198}{5} = 1.004$

Calculation of standard error for Group 1: $\frac{1.198(\max\ ) - 0.789(\min\ )}{2} \cong 0.205$

Calculation of percentage error for Group 1: $\frac{0.205}{1.004} \times 100 \cong 20.4\%$

IV. C. Graph

Below, Graph 1 presents the data from Table 2 on a cartesian coordinate system.



Graph 1: The relationship between the diameter of the hole inside the copper pipe and time taken to reach the ground.

IV. D. Linearizing the graph

Graph 1 presented an inverse relationship between the variables. To achieve a positive linear relationship, the root of the inverse of the time values must be taken. For error, the percentage error from Table 2 will be taken and applied to then new values. Below, Table 3 presents the diameter, the root of the inverse of the time values and their percentage and real uncertainty.

Diameter Group	Root of inverse values for time taken to reach the ground (s)	Percentage error	Real error
Group 1 (3.5cm)	0.998	20.4%	0.204
Group 2 (5.0cm)	1.115	12.9%	0.144
Group 3 (6.5cm)	1.203	22.6%	0.272
Group 4 (8.0cm)	1.328	27.9%	0.371
Group 5 (9.5cm)	1.624	25.3%	0.411

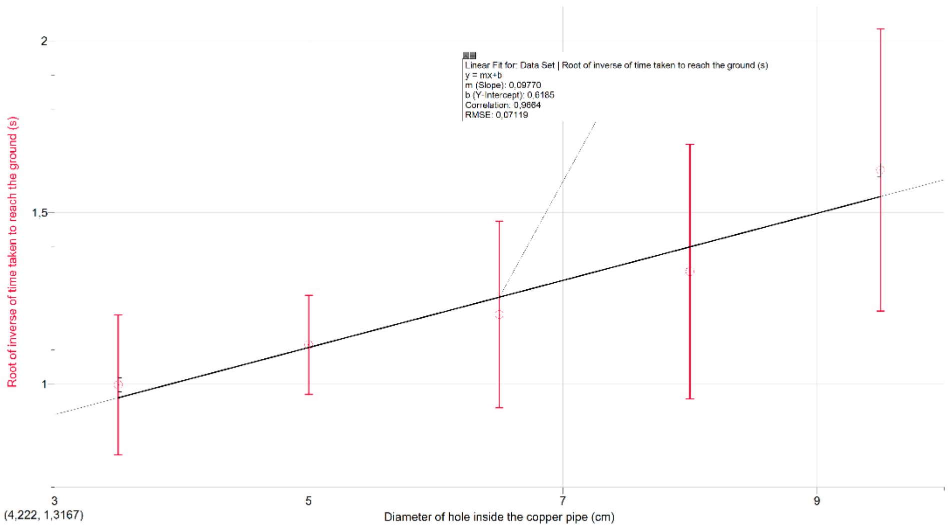
Table 3: The root inverse values for time, percentage error and real error.

Example calculations for root of inverse of time and real error

Root of inverse calculation for Group 1: $\sqrt{\frac{1}{1.004}} \cong 0.998$

Real error calculation for Group 1: $0.998 \times 0.204 \cong 0.204$

With the data from Table 3, Graph 2 below can be constructed where there is a linear and positive relationship between the variables.



Graph 2: The relationship between the root of inverse of time and the diameter of hole.

V. Discussion and evaluation

V. A. Evaluating the hypothesis

The hypothesis of this investigation suggested that the increase in the diameter of the hole inside the copper pipe would result in the neodymium magnet to fall faster since the distance between the copper pipe's surface and the magnet would increase. The data from the experiment indicates that this is true, where copper pipe holes with greater diameters resulted with the neodymium magnet reaching the ground in less time.

V. B. Limitations and strengths of the investigation

V. B. i. Strengths

Replicability: The low number of equipment and the simple procedure of the experiment allows for it to be repeated many times. By repeating the experiment, the effect of errors are decreased.

Control of external factors: The experiment has a number of external factors with all being controllable. By controlling the pipe dimensions and utilizing the same neodymium magnet for all trials, the experiment is only left with human error to influence the results.

V. B. ii. Limitations

The small range of diameters: This experiment only considered five different diameters (3.5, 5.0, 6.5, 8.0 and 9.5 cm). While this range allowed for suggestions to be made regarding the type and strength of the relationship between the diameter of the hole inside a copper pipe and the time for a magnet to reach the ground, the real relationship between the variables could be much different if a high enough range of diameters were considered.

The influence of human error: This experiment requires the measure of time which is measured by a stopwatch controlled by a human. Since the time for the neodymium magnet to reach the ground is between 0 and 2 seconds, the human reaction time error can have a high influence over the measured results. Even after repeating trials many times, human error can increase the range of the standard error greatly. A

The short height of the copper pipes: The investigation required all copper pipes regardless of the size of the hole inside them to have a uniform height of 30cm. This is a quite low height where in most trials the neodymium magnet reached the ground in less than a second.

The price of the copper pipes used: While most equipment such as a ruler, stopwatch and neodymium magnet are not expensive, the price of copper pipes with specific heights and thicknesses could be expensive. Copper pipes with the desired volume may not be available everywhere or have a high private production cost.

V. C. Addressing experimental errors

Systematic errors: No systematic errors were significant enough to be observed. Measurement instruments for time and volume were precise enough to neglect any systematic errors.

Random errors: Unfortunately, it can be suggested that random errors influenced the results of the experiment significantly. Due to the short height of the copper pipes and the speed of the magnet reaching the ground, human caused random errors resulted in high error margins as observed in Graph 1 and Graph 2 which increased the difficulty of predicting the relationship between the variables.

V. D. Suggestions to improve the experiment

Using taller pipes: As mentioned before, the height of 30cm for the copper pipes was short enough to contribute to experimental errors. If taller pipes were used, the neodymium magnet would take longer to reach the ground. This would decrease the influence of random human caused errors.

More trials: This investigation appointed five repetitions for each diameter group. However due to high influence of human error on the results, it was not enough. Having more trials would provide a more realistic result and would help to recognize the effect of human errors.

Greater range of diameters: Five different values for the diameters of the holes inside copper pipes were enough for the investigation to suggest a relationship, However, there could be a scenario where a much greater range of diameters were used and the observed relationship between the variables were much different compared to an experiment with on five different diameter values.

VI. Conclusion

The experiment to investigate the effect of increasing the diameter of the holes inside a copper pipe on the time for a neodymium magnet to reach the ground was conducted. The data from the experiment suggested that there was an inverse relationship between the size of the holes and time of the magnet to reach the ground. From data analysis it was suggested that the diameter of holes inside the copper pipe was had a positive linear relationship with the root of inverse of the time of the magnet to reach the ground. By observing and analyzing the experiment results, the hypothesis was accepted. However, due to the small scale of the experiment, human errors were found out to have influenced the experiment results significantly. The limitations and strengths of the experiment and the wider investigation were discussed. Random and systematic errors were addressed and suggestions to increase the accuracy of the experiment were provided.

VII. APPENDIX

References

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[10] YouTube. (2016). *YouTube*. Retrieved February 13, 2023, from Eddy and Lenz' Law Explained

Figures

Figure 1.1:

https://nationalmaglab.org/images/education/magnet_academy/history/pioneers/heinrich_lenz.png

Figure 1.2: https://cdn.britannica.com/44/68944-050-97DAD03B/Leon-Foucault.jpg?w=400&h=300&c=crop

Figure 1.3: https://media.springernature.com/lw785/springer-static/image/prt%3A978-0-387-30400-7%2F1/

Figure 2.1: http://hyperphysics.phy-astr.gsu.edu/hbase/electric/imgele/farlaw.png

Figure 2.2: http://hyperphysics.phy-astr.gsu.edu/hbase/electric/imgele/fday.png

Figure 2.3: https://media.geeksforgeeks.org/wp-content/uploads/20211115162649/Eddycurrent.jpg

Figure 3.1: https://www.200642at.com/wp-content/uploads/2021/08/depositphotos_74581243-stockphotohigh-voltage-power-transformer-768x795.jpg

Figure 3.2: https://www.globalrailwayreview.com/wp-content/uploads/train-wheels-with-brakes.jpg

Figure 3.3:https://www.gannett-cdn.com/-mm-/67c9fd5d920cd4816af0e03c5455f54dc61b77fc/c=0-7-597- 344/local/-/media/2015/02/20/USATODAY/USATODAY/635600517092962599-f16-crash2.JPG? width=597&height=337&fit=crop&format=pjpg&auto=webp

Figure 3.4: https://st2.depositphotos.com/3692301/8738/i/950/depositphotos_87380874-stock-photo-car-speed-meter.jpg

Figure 4.1: https://pbs.twimg.com/media/DUuGOdhXcAE4Sxc.jpg