Investigating the relationship between the number of turns in a coil and induced current.

1. Research Question

How does changing the number of turns in a copper coil affect the measured induced current when a neodymium magnet passes through the center of the coil at a constant velocity?

2. Introduction

Michael Faraday was the first to discover electromagnetic induction in the 1830s. Faraday discovered that moving a permanent magnet in and out of a coil or a single loop of wire caused an Electromotive Force, or emf, which resulted in a voltage and hence a current to be generated inside of a coil.[1]

Michael Faraday's stated "that a voltage is induced in a circuit whenever relative motion exists between a conductor and a magnetic field and that the magnitude of this voltage is proportional to the rate of change of the flux".

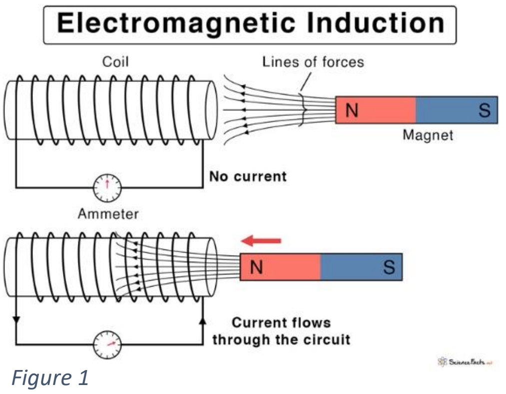

Figure 1

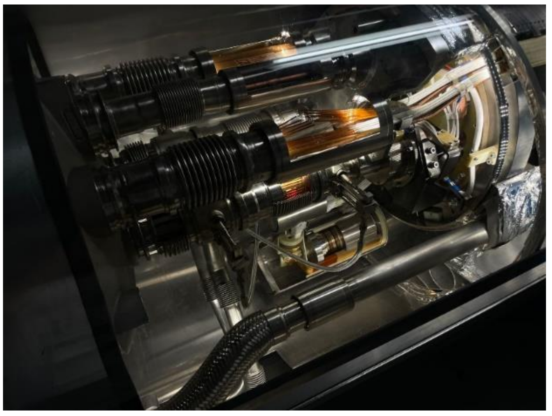

Figure 2

Figure 1 – Shows a magnet approaching a coil of wire, with an ammeter connected to it[2]

Figure 2 – Shows a picture taken by the originator of this IA, showing a part of the CERN particle accelerator

My first interaction with electromagnetism was during a middle school physics class, in which we did multiple experiment involving electromagnetism, and one of them particularly caught my attention. The experiment involved coils of copper wire wrapped around an iron core, and a battery connected to each end of the wire, thus creating a solenoid and creating a magnetic field around it. After creating the solenoid, we would test to see if different metals were magnetic by approaching each one near the solenoid. This experiment sparked curiosity about electromagnetism, and since then I've always thought that electricity and electromagnetism were very interesting topics, despite being the hardest and most challenging topics to wrap my head around and truly understand. However, recently, when brainstorming ideas for my IA, I went through the IB Physics Syllabus thoroughly, and stepped upon a whole chapter about electricity and magnetism, and it brought many memories back, and after

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[1] Anon, 2020. Electromagnetic induction and faradays law. *Basic Electronics Tutorials*.

2 Anon, 2021. Electromagnetic induction: Definition, examples, & applications. Science Facts.

further research based on my interest, it allowed me to establish a connection between electromagnetism and many real-world applications: such as metal detectors, generators, motors, transformers and even electric bells. I consequently decided to investigate electromagnetism and was especially curious about the effect of changing the number of turns of the coil on the induced current. More recently, I visited CERN, which is a particle accelerator, I learnt that a particle accelerator was using electromagnetism in order to accelerate the particles to 99.9% of the speed of light, which was an even bigger incentive to further develop my understanding of this topic. (See figure 2)

"Electromotive force (EMF) is equal to the terminal potential difference when no current flows. EMF and terminal potential difference (V) are both measured in volts, however they are not the same thing. EMF (ϵ) is the amount of energy (E) provided by the battery to each coulomb of charge (Q) passing through."[3]

An emf is induced in a conductor whenever the magnetic **flux linkage**[4] through the conductor changes. Faraday's Law states that the magnitude of the induced emf in a conductor is directly proportional to the rate of change of magnetic flux linkage and the number of turns.[5] In simpler terms, a coil experiences an induced current when the magnetic field around the coil experiences change.

Faraday's law states that:

$$\varepsilon = \mathrm{N}\frac{\Delta\Phi}{\Delta \mathrm{t}}$$

$$\varepsilon = \text{Electromotive Force (V)}; N = number\ of\ turns(N);$$

$$\Delta\Phi = \text{change in magnetic flux density(Webers)};$$

$$\Delta \mathrm{t} = \text{change in time(s)}$$

The **flux linkage** is the quantity of magnetic flux enclosed by a loop of conductor. The induced emf depends on the speed the conductor is moving, the magnetic flux linkage with the conductor, and the direction of motion through the field.

$$\text{magnetic flux linkage} = N\Phi$$

$$N = number\ of\ turns;\ \Phi = \text{magnetic flux density}$$

Here, we can see that the magnetic flux linkage is directly proportional to the number of turns. Which is what will be investigated in this experiment. A H

"*When a magnetic field line passes inside a loop created by a conductor, it is said to be linked by that conductor. If the conductor is made out of multiple loops, for example a solenoid, then this magnetic field will be linked by each loop in the solenoid. This means that for a solenoid, the magnetic flux*

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3 Anon, Physics - electromotive force. University of Birmingham.

4 Anon, Magnetic Fields. Isaac Physics.

5 OpenStax, 2020. Induced Emf and Magnetic Flux Induced Emf and Magnetic Flux. OpenStax CNX.

linkage is the magnetic flux passing through the cross-sectional area of the coil (the magnetic flux through a single turn of the coil Φ = BA) multiplied by the number of turns N in the coil."[6]

Faraday's law says that a changing magnetic field produces an electric field. If charges are free to move, the electric field will cause an emf which drives a current. If a loop of wire is placed in a magnetic field so that the field passes through the loop, a change in the magnetic field will induce a current in the loop of wire. By ohm's law, the current in the circuit is proportional to emf across the conductor. Therefore, the emf drives a current and thus both increases with increase in number of turns.

$$V = IR$$

$$V = voltage(V); I = current(A); R = resistance(\Omega)$$

"The larger the area means more field enclosed and so the higher the voltage. The faster the changes, the greater is the induced voltage"[7]

3. Apparatus

- **Micrometer** (range: 0-25mm) (± 0.0002 cm)
- **Ruler** (range: 0.1cm-30cm) (± 0.05cm)
- **Hollow plastic cylinder** of height 7cm
- **Multimeter** (range: 0-10A) (± 0.001 mA)
- **Copper wire** (Diameter of wire is 0.300mm (± 0.001cm) was measured using micrometer, and taking the average of multiple measurements at different places on the wire
- **5 circular neodymium magnets** (Diameter of one magnet is 1.2cm (± 0.05cm))(Height of the 5 magnets combined is 4cm(± 0.05cm))(Height of one magnet is 0.8cm (± 0.05cm))
- **Long hollow cylinder** ("Steering Cylinder") (Height of 20.5cm, this cylinder will allow for the distance from which the magnet will be dropped to stay constant.)
- **Tape** will be used to stick the steering cylinder on top of the cylinder with the coil
- **Electrical wires (**± 0.05cm) (Length: 36cm)
- **2 Crocodile Clips**

4. Method

4.1 – Variables

Independent variable: the number of copper wire turns around the plastic cylinder **(Range: 30 - 180turns)**

Dependent variable: Induced current through the coil

6 Anon, Magnetic Fields. Isaac Physics.

7 Anon, Chapter 25: Electromagnetic Inductance. University of Oregon.

Control variables:

1. The Magnet

   a) Reason: A magnet has a specific magnetic field around it, since this magnet's magnetic field will interact with the coil's magnetic flux, changing the magnet will impact this interaction and thus impact the induced current.

   b) Method: the same 5 circular neodymium magnets piled on top of each other will be used when dropped inside the coil, and no other magnets will be used apart from these.

2. The height from which the magnet is dropped

   a) Reason: If the same coil of wire passed through the same magnetic field but its speed or velocity is increased, the wire will cut the lines of the magnetic flux at a faster rate so more induced emf would be produced and thus more current. As shown above, the induced emf is directly proportional to the rate of change in magnetic flux, a faster magnet would result in a lower change in *t* and thus a higher change in magnetic flux, as there is an inverse relationship between the induced emf and the change in time. Furthermore, the last loop will contribute more to the induced emf as the magnet is moving faster.

   b) Method: A cylindrical hollow tube with a path in the middle big enough for the magnets to pass through was taped and leveled on top of the coil wrapped in copper wire. The magnet was then dropped from a known fixed, distance, which resulted in approximately the same velocity every repeat and trial, and thus the same time taken from the magnet to hit the bottom of the coil.

3. The distance between the coils.

   a) Reason: If the coils are tightly bunched together, it might give a different value than if the coils were equally spaced. As the magnetic flux density would be different.
   b) Method: The distance between each loop of copper wire will be kept approximately the same, for every repeat, and trial.

4. Location of the experiment

   a) Reason: Earth has a magnetic field and so its field may have an impact on the result of the magnetic flux density of the apparatus.

   b) Method: The experiment is carried out at the exact same location every trial in order to maintain the interference the Earth's field might have on the experiment.

4.2 <u>Instructions</u>

1. Set up the apparatus as shown in Figure 2

    a) Ensure the coil has tight turns and turns of equal spaces, use a good quality copper wire, or else it might break while making the turns.
    b) Using two wires, connect a crocodile clip to one end of each cable, and proceed to connect the other extremity of the wires to the multimeter. One wire should connect to the terminal called "COM", usually labelled in black, and the other cable should be connected to the terminal labelled "mA" as we trying to measure current.
    c) Proceed to connect one of each crocodile clips to both of the free ends o the coil. Whether you connect the "COM" cable to the right or left free end, or you connect the "mA" cable to the right or left free end, does not impact the results in any significant way. Make sure however that the teeth of the crocodile clips are well tightened and clasped around the wire.
    d) The multimeter should then be turned on the most sensitive mode of the "Ampere" section of the multimeter. The most sensitive mode being the mode which allows for the most decimal places to be shown.

2. Take the magnets and place them inside the "steering cylinder" which is taped above the coil, however, do not release the magnets yet. Insert the magnet until the top of the magnet is flush with the top of the steering cylinder. When, you are ready to drop the magnets inside the coil, release, and do not push it down or hold, release it simply, without adding any external force onto the magnet.
3. The ammeter will show values of the current changing. Record the peak value from the ammeter.
4. Repeat step 2 – 3- 4 other times, so you have 5 total repeats
5. Repeat step 1- 4 with varying number of turns (30, 60, 90 ,120, 150, 180) turns

Figure 3 - Picture taken on the day of the physical investigation, displaying the apparatus used. Copper coil used to make turns around cylinder, to create coil, with steering cylinder taped on top, and the multimeter connected to both ends

4.3 <u>Safety Assessment</u>

A couple of potential safety concerns can arise from this investigation. The first one being the improper use of the neodymium magnets. Neodymium magnets are very strong magnets, with very strong magnetic fields surrounding them. If any other magnets or magnetic objects around enter the magnetic field of the magnets, they will be attracted to the magnet used for this experiment. If, for example another cylindrical magnet is laying around, and the magnet used is getting too close to its magnetic field, it will be strongly attracted to it, and as a result it can pinch the skin or result in other type of injuries. Similarly, if scissors, blades, or any magnetic object is laying around it can cause serious bodily injuries, to the experimenter and the people around. The experimenter should consequently, clear the area around of any risky object such as scissors or blades, and be careful not to have other magnets laying around. Current induced is too low to risk any fire or overheating hazards.

5. Raw Data

TRIALS	Number of turns	Induced Current (mA) ± 0.001				
	Repeats	1	2	3	4	5
1	30	0.060	0.070	0.083	0.053	0.089
2	60	0.159	0.149	0.169	0.180	0.175
3	90	0.234	0.312	0.232	0.242	0.287
4	120	0.336	0.340	0.349	0.350	0.349
5	150	0.389	0.481	0.381	0.463	0.424
6	180	0.548	0.521	0.537	0.498	0.512

Table 1 - Raw data of the experiment, showing the number of turns in relation with the respective induced current, repeat and trial number are also present

6. Processed data

Trials	N. of turns	Average (mA) ± 0.001	Absolute Uncertainty (± mA)	Relative Uncertainty as a %	Total Absolute Uncertainty	Standard Deviation
1	30	0.071	0.018	26.76	0.019	0.015
2	60	0.166	0.016	9.92	0.017	0.012
3	90	0.261	0.040	15.68	0.041	0.036
4	120	0.345	0.007	2.32	0.008	0.006
5	150	0.428	0.050	11.93	0.051	0.044
6	180	0.523	0.025	4.97	0.026	0.020

Table 2 - Processed data showing the calculated average induced current in the solenoid dependant on the number of turns, and showing the calculated Absolute Uncertainties, Relative Uncertainties (%) and the Total Absolute Uncertainties

Standard deviation not used because usually for big sample, and rather use big uncertainty

<u>Sample Calculations for Table 2</u>

Average at N = 30:

$$\frac{\bar{x} = x_1 + x_2 + \cdots x_N}{N}$$

$$\frac{\bar{x} = 0.060 + 0.70 + 0.83 + 0.53 + 0.089}{5} = 0.071$$

$\bar{x} = average;$ *N = number of values*

Absolute Uncertainty at N = 30:

$$\Delta x = \frac{x_{max} \quad - x_{min}}{2}$$

$$\Delta x = \frac{0.083 - 0.053}{2} = 0.018$$

$\Delta x = absolute\ uncertainty;\ x_{max} = maximum\ value\ in\ data\ set;$
$x_{min} = minimum\ value\ in\ data\ set$

Relative uncertainty at N = 30:

$$Relative\ Uncertainty = \frac{Total\ \Delta x}{x} * 100$$

$$\text{Relative Uncertainty} = \frac{0.019}{0.071} * 100 = 26.76\%$$

$$\Delta x = Absolute\ Uncertainty;\ x = value$$

Thus, the Total Absolute Uncertainty at N = 30 can be found using this equation:

*Standard Uncertainty is given by the multimeter used: 0.001

$$Total\ Absolute\ Uncertainty = Absolute\ Uncertainty + Standart\ Uncertainty$$

$$Total\ Absolute\ Uncertainty\ =\ 0.018\ +\ 0.001\ =\ 0.019$$

Standard Deviation at N=30:

$$Standart\ Deviation = \sqrt{\sum_{i=1}^{N} \frac{(x_i - \bar{x})^2}{N-1}}$$

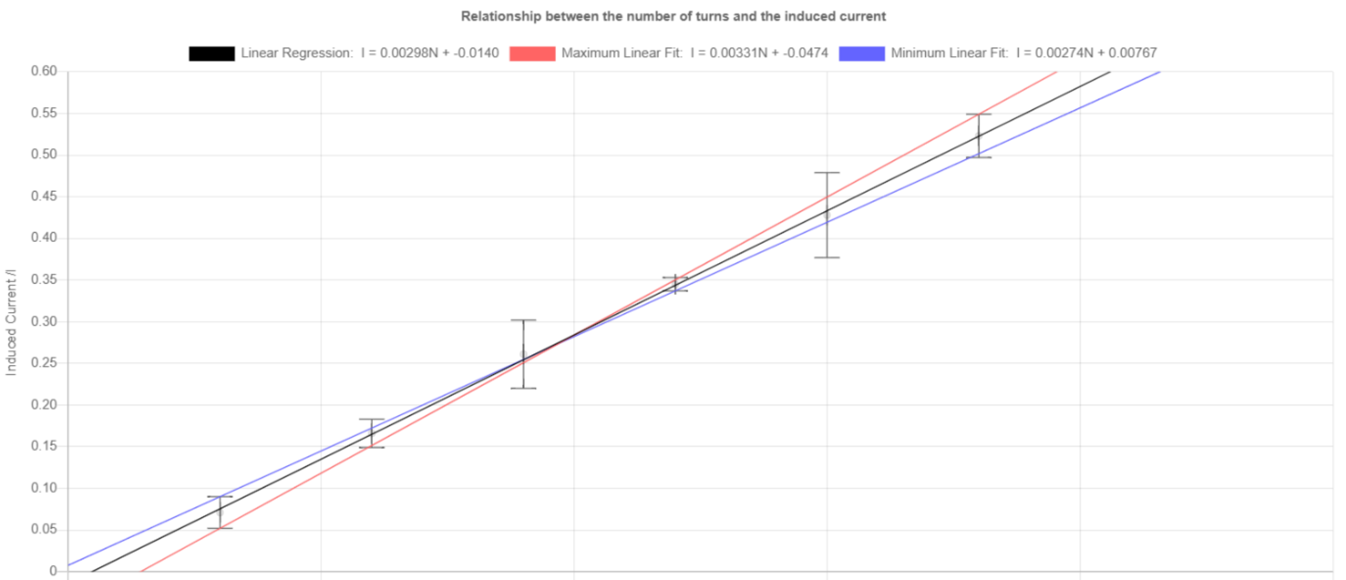
Standard Deviation = $\frac{(0.060-0.071)^2+(0.070-0.071)^2+(0.083-0.071)^2+(0.053-0.071)^2+(0.089-0.071)^2}{5-1} = 0.15$

$$N = number\ of\ values;\ x_i = value\ in\ the\ dataset;\ \bar{x} = mean\ value;$$

$$i = position\ of\ the\ value\ in\ the\ dataset$$

Here I decided not to use standard deviation to calculate my total absolute uncertainty, as I would rather use the biggest calculable uncertainty using my values. Moreover, standard deviation is usually used for very large samples sizes, while this experiment only contains 5 repeats per trial, which would not result in adequate values using Standard Deviation.

[8]7. Graphical Interpretation



Graph 1 - Linear graph showing the relationship between the number of turns and the induced current, with uncertainties considered. Three trendlines present. Maximum line of best fit, Minimum Line of best Fit and Normal trendline

This graph (Graph1) was plotted using the processed data. The x-axis represents the number of turns in the solenoid (N), while the y-axis represents the magnitude of the induced current(I). The error bars here represent the total absolute error in the measured induced current. From this graph, a clear, direct relationship ca be observed between the number of turns (N) on the solenoid and the current through flowing through the solenoid. As the number of turns increases, the magnitude of the induced current also increases. The graph above illustrates the line of best fit for the data, indicated by the black trendline in the middle, with a gradient of 0.00298; the maximum gradient is indicated by the red trendline located on the bottom of the graph, with a gradient of 0.00331; and the minimum gradient indicated by the blue trendline, located on the top of the graph, with a gradient of 0.00274. The line of best fit is given as: I = 0.00298N+ 0.0140.

[8] http://www.beepboopmachines.com/g/index.html

The total uncertainty in the gradient of the line of best fit is calculated using:

$$\frac{Mmax - M_{\min}}{2}$$

Where: M_{max} is the maximum gradient; and M_{min} is the minimum gradient

The total uncertainty of gradient = $(0.00331 - 0.00274)\ X\ 0.5 = \pm 0.000285\ \approx\ \pm 0.00029$

That gives the gradient of the line of best fit 0.00298 to be 0.03000 $\pm$ 0.00029

The percentage error of the gradient = $\frac{0.000285}{0.00298}$ x 100 = 9.56% ≈ 9.6%

Thus, the percentage error of the experiment is 9.6%

7. Comparison

According to Faraday's law of electromagnetism, emf induced is given by:

$$\varepsilon = \mathrm{N}\frac{\Delta\Phi}{\Delta \mathrm{t}}$$

As the theory suggests there is a direct relationship between the induced EMF and the number of turns

$$\varepsilon \propto \mathrm{N}$$

The data and values collected during this experiment demonstrate a strong, linear relationship between the number of turns on the solenoid and the induced current flowing through the solenoid demonstrating that the theoretical relationship correlates with the achieved proportional direct relationship, showing that the values and relationship found, is relevant and accepted within the scientific context and community

9. Conclusion

By analysing the graph, it can be concluded that there is a clear and direct relationship between the number of turns in the coil(N) and the Average Induced Current (I) through the coil. The induced current increases, when the magnet passes in the core of the coil, as there are more turns around the coil. Thus, the original research question (How does changing the number of turns on a coil affect the induced current when a magnet passes through it?") Can be answered by: increasing the number of turns on the coil, when a magnet passes through it at constant speed, also results in a increased induced current generated. The line of best fit indicates a strong linear correlation between the number of turns and its corresponding the induced current. The final gradient is calculated to be: 0.03000 $\pm$ 0.00029. The clear direct relationship between the number of turns and the induced current, as a result of the graph plotted, can be explained by referring to Faraday's Law of Induction:

$$\varepsilon = N\frac{\Delta\Phi}{\Delta t}$$

As displayed in the equation the magnitude of the induced emf is directly proportional to the number of turns in the coil. As $\varepsilon \propto N$, the greater the number of turns (N), the greater the magnitude of the induced emf will be, when a magnet passes through it.

10. Evaluation

The percentage error of the average induced current was calculated using the following equation:

$$Relative\ Uncertainty = \frac{Total\ \Delta x}{x} * 100$$

As calculated in table 2, the table showing the processed data, the Total Relative Uncertainty of the current is expressed as a percentage. Here is a sample calculation of how the Relative Uncertainty was calculated.

Relative uncertainty at N = 30:

$$Relative\ Uncertainty = \frac{Total\ \Delta x}{x} * 100$$

$$\text{Relative Uncertainty} = \frac{0.019}{0.071} * 100 = 26.76\%$$

$$\underline{\Delta x = Absolute\ Uncertainty; x = value}$$

This calculation was done for every consequent number of turns.

For N = 30: %error of I = 26.76%

For N = 60: %error of I = 9.92%

For N= 90: %error of I = 15.68%

For N = 120: %error of I = 2.32%

For N = 150: %error of I = 11.93%

For N = 180: %error of I = 4.97%

Therefore, Max % error of I = 26.76% and Min % error of I = 2.32%

By analyzing the graph, I noticed that the line of best fit was not going through the origin, suggesting a potential systematic error. However, it has to be noted that the origin is within the uncertainty of the origin, meaning that there we cannot conclude with a 100% certainty that there was a systematic error during the experiment. Random errors were also present in this experiment.

One source of random and systematic error could have been the **height from which the magnet was dropped**. As indicated in the equation the induced emf is directly proportional to the rate of change in magnetic flux. Here, the height from which the magnet is dropped plays a crucial part in the accuracy of this experiment. A change in height from which the magnet is dropped, would result in a different velocity. For example, if the magnet was dropped a centimeter higher than the normal declared height, the velocity of that magnet when entering the coil would have been greater and thus would travel through the coil faster, resulting in a rate of change in magnetic flux to increase, consequently resulting in an increase in the induced emf, independent of the number of turns. This error is of **medium significance**. The maximum % error for current was of 26.76%, which is a non-negligible percentage, which shows that the values were greatly affected by systematic errors. This could highly affect the accuracy of the values of the measures induced current. To internalize this error, or reduce it, attach the magnet that should be dropped to **a clamp** that stays at constant height. When ready to release the magnet, simply reduce the pressure applied by the clamp on the magnet and let it fall in the coil. This should ensure that the magnet is constantly travelling at the same velocity as before, when passing through the coil.

Another source of random error and systematic error, which strongly links back to the height at which the magnet was dropped, would be the **natural movement of the body** when dropping the magnet through the tube. If the person dropping the magnet through the tube accidentally applies a force on the magnet before dropping, the velocity would be higher than previously. Which, just like for the height from which the magnet is dropped, will result in a greater velocity when the magnet passes through the coil, which, in turn, will result in a higher induced current, and thus skew the data, as velocity is not kept constant throughout the experiment. This error is of l**ow significance.** A potential solution to this problem would again, to be using a clamp to release the magnet rather than human fingers, this would totally remove the possibility of an external unwanted force acting on the magnet, and thus affecting the velocity. However, this could potentially worsen the error, as if the magnet is dropped at a certain angle it could lead to it touching the sides of the coil and affecting the velocity too.

Another source of random error would be the **heat generated** in the coil due to the current flowing through it. The experiment is carried out continuously, and eventually, the induced current heats up the coil, consequently leading to an increase in the resistance of the circuit, and thus leading to a decrease in the current measured by the multimeter. This error is of **low significance**, in this experiment, as we cannot see a significant change in gradient, or a non-proportional increase in current compared to the number of turns, leading me to believe that the induced current, did not in fact lead to a noticeable, significant increase in temperature and thus resistance. If, however, the experiment was done with more repeats and more trials, heat would become a larger source of error. The maximum % error for current was 26.76%, leading me to believe that, other source of errors must have come into place rather than temperature. Moreover, the maximum % uncertainty was reached during the first trial at N=30, almost completely eliminating the source of error aforementioned. However, as mentioned, if this experiment was to take place for an extensive period of time, temperature would become an issue. A solution to this, would be to set a **time interval** for the circuit to cool down after each set of data measured, and thus reducing the effect of heat on the induced current. In order to get even more accurate values, a **thermal camera** could be used. Measure the temperature of the coil before starting the experiment, and after the first repeat, measure it again using the camera, and wait until the original temperature is reached before starting another repeat or trial. Measure multiple points of the coil. In case the coil gets colder than original, heat it up by inducing current.

Another source of systematic error would be the **sensitivity of the multimeter**. Sometimes throughout the experiment, when the magnet was dropped through the coil, the multimeter would not react, and would simply display .000. Obviously, it is impossible for the induced current to be non-existent at this point as the magnet had just been through the coil. It did not impact the result, as I would record these values to create a frequency table of how frequent they are, but I would simply consider them as outliers, and not process them. However, this could cause a problem, as even though the current was shown to be 0, some current was still induced through the coil, this in turn, could impact the warmth of the coil, and its resistance. This error is of **low significance**, however, when I noticed this happening through the experiment, I thought that the multimeter was simply defective, and so I changed it, but the same problem occurred. I then decided to use a digital ammeter that would record the values directly on my computer, however I encountered difficulties with the software of the ammeter, and decided to continue using the ammeter. A potential solution to this, could have been, to simply use a **more sensitive multimeter, or an higher quality multimeter**. However, this was not available on site during testing. Another potential solution might have been to do 10 trials, and then take the maximum value of these, rather than an average, as it might be difficult to get a reading that is simultaneous with the magnet entering the coil.

Some of these errors are affected are affected by both systematic errors and random errors to some extent.

Throughout the experiment I encountered an issue. At the beginning of the experiment, I realized that the steering cylinder, the one from which the magnet was dropped from was one taped incorrectly and was slightly angled, which affected the height from which it was dropped. When I went to check the steering cylinder was straight, using a geo triangle, I noticed the steering cylinder at the top was angled differently than from the bottom, surely due to its weight. I had to restart the experiment, as the values were not correct. To fix the issue I simply added more tape at its base, securing it more tightly with the coil.

The value of the total systematic error in the investigation is 0.0140. However, the y-intercept is contained within the random uncertainty of the origin, there is therefore no evidence that this is a systematic error. Considering, the percentage error in the gradient is 9.6%, I can conclude that there is a relatively low level of error is this experiment. However, to improve on this experiment, the amount I modify the number of turns could be increased, thus increasing the number of trials, and thus the range of values. More repeats could also be done for a more reliable average, and the precision of the multimeter could be increased to reduce the % uncertainty of the values used and measured. A digital ammeter with a computer could be used to the the ammeter readings at very short time intervals, so that I could hopefully be able to plot and determine the maximum value for the current.

This experiment opens many more questions about electromagnetic induction, and thus this experiment could be extended, by using different materials for the wire that is used to make up the coil. Copper having a low electrical resistance, means that by using different wires of similar electrical resistance, such a pure silver and aluminum, we can be surer and more confident in the universal use of Faraday's equation, and that it is not exclusive only to a coil made of copper.

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