Physics Extended Essay

Topic:

Eddy Current Brakes

Research Question:

To determine how varying strengths of an electromagnet affect the time for an eddy current brake to come to rest

Word Count: 4000

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Glossary

Term	Definition
Electromagnet	"device consisting of a core of magnetic material surrounded by a coil through which an electric current is passed to magnetise the core."[1]
Solenoid	"a uniformly wound coil of wire in the form of a cylinder having a length much greater than its diameter."[2] A solenoid around an iron core is called an electromagnet.
Magnetic flux	"Magnetic flux is a measurement of the total magnetic field which passes through a given area"[3]
Electromotive force (emf)	"energy per unit electric charge that is imparted by an energy source, such as an electric generator or a battery."[4]
Right-hand rule	The right-hand rule is a hand sign used to find either the direction of a magnetic field or the direction of a moving charge. By pointing the right thumb in the direction of the current in the wire and curling the remaining fingers, the fingers will be curled in the same direction as the magnetic field around the wire.[5]
Normal vector	"The normal vector (often called the "normal") to a surface is a vector which is perpendicular to the surface at a given point."[6]

[1] Britannica (2014, January 27). *electromagnet*. Retrieved from: https://www.britannica.com/science/electromagnet. Accessed: 13.11.22

[2] Britannica (2022, October 13). *Solenoid*. Retrieved from: https://www.britannica.com/science/solenoid-electronics. Accessed: 13.11.22

[3] Khan Academy (2022). *What is magnetic flux?*. Retrieved from: https://www.khanacademy.org/science/physics/magnetic-forces-and-magnetic-fields/magnetic-flux-faradays-law/a/what-is-magnetic-flux. Accessed: 19.10.22

[4] Britannica (2022, September 27). *electromotive force*. Retrieved from: https://www.britannica.com/science/electromotive-force. Accessed: 13.11.22

[5] Khan Academy (2022). *Using the Right-Hand Rule*. Retrieved from: https://www.khanacademy.org/test-prep/mcat/physical-processes/magnetism-mcat/a/using-the-right-hand-rule. Accessed: 13.11.22

[6] Wolfram (2022, November 4). Normal Vector. Retrieved from: https://mathworld.wolfram.com/NormalVector.html. Accessed: 13.11.22

Abstract

In this investigation the relationship between magnetic flux through a disk and the time for the disk to come to rest are explored to determine the effect that the strength of an electromagnet has on the time for an eddy current break to come to rest. To achieve this, the disk is rotated to a maximum velocity and then an electromagnet is powered. The current the electromagnet receives is varied in order to change the strength of the electromagnet. Eddy currents are induced within the disk due to Faraday's Law of Induction and Lenz's Law. These eddy currents cause the disk to decelerate and come to rest. The outcome of the investigation, based on collected data, is that as the magnetic flux through the disk is increased, the time for the disk to come to rest decreases. Consequently, it was determined that there is a directly proportional relationship between time and negative magnetic flux. Hence, as the strength of the electromagnet is increased, the time for the disk to come to rest decreases.

I. General Overview

Background Information

Eddy Currents in The Real World

In 1855, Léon Foucault, a French physicist, discovered the concept of eddy currents, specifically, their braking properties.[7] He discovered that when a copper disk is placed between the poles of a magnet, the force required to rotate the disk at the same velocity increases. The first applications of eddy currents were discovered in 1879 when David E. Hughes[8], a British-American inventor, used Foucault's concept to successfully carry out metal sorting tests. Later, in 1887, Granville T. Woods, a self-taught American inventor, invented the first model of the electromagnetic brake designed for use in trains.[9] However, they were only implemented as emergency systems in the early twentieth century. Since then, the diversity of applications of eddy currents has dramatically increased, whilst the fundamental principles behind its function have remained the same.

Today, eddy current brakes are popular for their quiet, frictionless, and economical advantages. Eddy current brakes have a wide range of applications, for example, they are used in many locomotives, especially in high-speed electric trains such as the German InterCity Express

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[7] Forrister, T (2019, March 6). *How Eddy Current Braking Technology Is Freeing Us from Friction*. Retrieved from: https://www.comsol.com/blogs/how-eddy-current-braking-technology-is-freeing-us-from-friction/. Accessed: 28.08.22

[8] Forrister, T (2019, March 6). *How Eddy Current Braking Technology Is Freeing Us from Friction*. Retrieved from: https://www.comsol.com/blogs/how-eddy-current-braking-technology-is-freeing-us-from-friction/. Accessed: 28.08.22

[9] Thomas Publishing Company, (2022, August 28). *All About Electromagnetic Brakes: How They Work and Types.* Retrieved from: https://www.thomasnet.com/articles/machinery-tools-supplies/all-about-electromagnetic-brakes/. Accessed: 28.08.22

and the Japanese bullet.[10] In contrast with conventional friction brakes, they are frictionless which avoids the need for regular maintenance and repair. According to Chris Woodford, a British science writer, “It's estimated that switching an electric train from friction brakes to eddy-current brakes could halve the cost of brake operation and maintenance over its lifetime.”[11] Other applications of eddy current brakes in today’s society include aircrafts, roller coasters, gym equipment, and in industrial equipment.[12]

To understand how eddy current brakes function, one must have a basic understanding of Faraday’s Law of Induction and Lenz’s Law. Faraday’s law determines how a changing magnetic flux through a loop induces a current within the loop and Lenz’s law determines the direction of this induced current.

Faraday’s Law of Induction

In 1831, Michael Faraday, an English Physicist and Chemist, discovered electromagnetic induction and formulated his law of induction.[13] Faraday’s Law of Induction states that “the magnitude of the induced emf is proportional to the rate of change of magnetic flux linkage”[14]. This principle is represented in the formula $\varepsilon =- N\frac{d\phi}{dt}$ where ε is emf or induced voltage, N is

[10] Forrister, T (2019, March 6). *How Eddy Current Braking Technology Is Freeing Us from Friction*. Retrieved from: https://www.comsol.com/blogs/how-eddy-current-braking-technology-is-freeing-us-from-friction/. Accessed: 28.08.22
[11] Woodford, C (2021, March 23). *Eddy Current Brakes*. Retrieved from: https://www.explainthatstuff.com/eddy-current-brakes.html. Accessed: 28.08.22
[12] Head Rush Technologies (2021). *5 Applications of Eddy Current Brakes*. Retrieved from: https://headrushtech.com/blog/5-applications-eddy-current-brakes/. Accessed: 28.08.22
[13] Britannica (2022, July 11). *Faraday’s law of induction.* Retrieved from: https://www.britannica.com/science/Faradays-law-of-induction. Accessed: 20.08.22
[14] Lin, D (2016). *Topic 11: Electromagnetic induction (HL).* Retrieved from: https://ibphysics.org/topic11/. Accessed: 28.08.22

the number of loops, $d\phi$ is the change in magnetic flux and dt is the change in time.[15] Jim Lucas, a physics graduate from Missouri State University, explains that Faraday's law describes how a moving magnet with a magnetic field generates an induced electric current in a conductor, and conversely, how an electric current can produce a magnetic field.[16]

As a magnet travels towards a loop of wires, the magnetic field strength at the loop increases, and thus the magnetic flux in the loop increases. This causes a current to be induced in the loop. The change in current can be recorded using the galvanometer as demonstrated in *figure 1*.

As the magnet travels away from the loop, the magnetic field strength at the loop decreases, and thus the magnetic flux in the loop decreases. This results in the induced current flowing in the opposite direction as before.

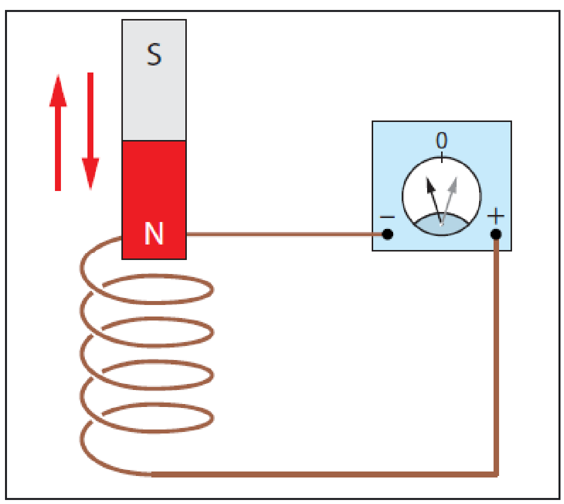

figure 1: Demonstration of Faraday's Law of Induction [17]

[15] Britannica (2022, July 11). *Faraday's law of induction.* Retrieved from: https://www.britannica.com/science/Faradays-law-of-induction. Accessed: 20.08.22
[16] Lucas, J (2022, February 18). *What is Faraday's law of induction?*. Retrieved from: https://www.livescience.com/53509-faradays-law-induction.html#section-electricity. Accessed: 28.08.22
[17] Tsokos, K, A, (2014). *Physics for the IB Diploma*. Cambridge, UK: Cambridge University Press. Edition six

Lenz's Law

In 1834, Heinrich F. E. Lenz, a Russian physicist, formulated his law regarding induced electric currents.[18] Lenz's law states that "the induced emf acts in the direction such that the current induced opposes the charge which caused it."[19] Lenz's Law justifies the importance of the negative sign in the previous formula, $\varepsilon = - N\frac{d\phi}{dt}$, as it represents the direction in which the induced emf is acting.

As a magnet with a magnetic field (shown with a green arrow in *figure 2a*) travels towards a loop of wire, the magnetic field at the loop is getting larger, and thus the magnetic flux in the loop increases. Following Lenz's law, the induced current must oppose the increase in flux. To achieve this, the induced current must create a temporary magnetic field in the opposite direction to that of the magnet, this repels it (shown with a blue arrow in *figure 2a*). The direction in which the current flows can be determined using the right-hand rule, in this case it is counterclockwise.

As the magnet travels away from the loop (shown in *figure 2b*), the opposite happens, the magnetic flux in the loop decreases. Following Lenz's law, the induced current must oppose the decrease in flux. To accomplish this, the induced current must create a temporary magnetic field in the same direction to that of the magnet, this attracts it (shown with a blue arrow in *figure 2b*). The direction in which the current flows, can again be determined using the right-hand rule, in this case it is clockwise.

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[18] Britannica (2020, May 29). *Lenz's law*. Retrieved from: https://www.britannica.com/science/Lenzs-law. Accessed: 28.08.22

[19] Lin, D (2016). *Topic 11: Electromagnetic induction (HL).* Retrieved from: https://ibphysics.org/topic11/. Accessed: 28.08.22

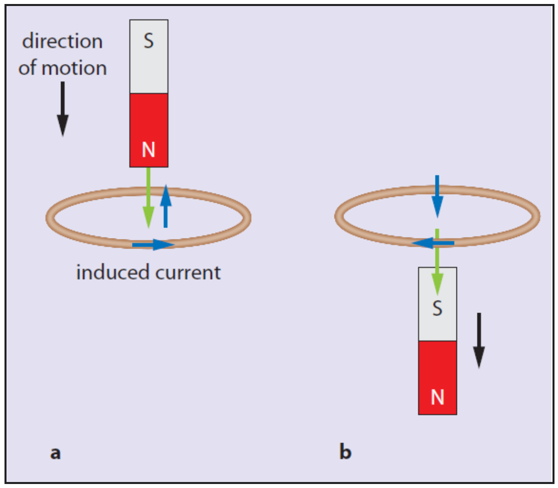


figure 2: Demonstration of Lenz's Law [20]

Eddy Currents

In this investigation a rotating disk will be brought to rest using eddy currents induced from an electromagnet. The electromagnet will create a magnetic field once current flows through its solenoid. Because the disk is rotating and the electromagnet is stationary, Faraday's Law of Induction and Lenz's law are applicable. The ability to control the application of these principles is the fundamental concept behind real world eddy current braking systems. This investigation will model these real world braking systems and will explore how varying strengths of an electromagnet affect the time for a disk to come to rest. *Figure 3* will be used to explain how the investigation will combine these laws in order to achieve this.

[20] Tsokos, K, A, (2014). *Physics for the IB Diploma*. Cambridge, UK: Cambridge University Press. Edition six

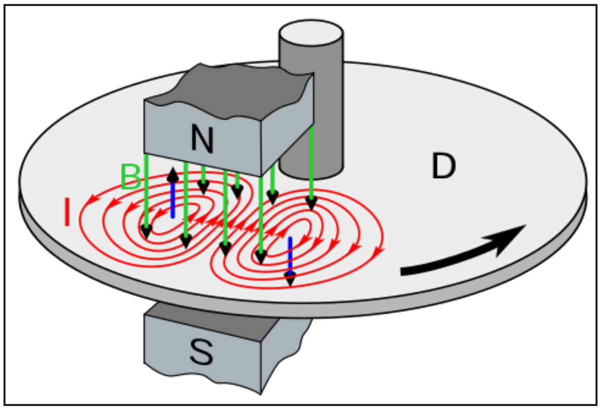


figure 3: Demonstration of eddy currents on a rotating disk - Faraday and Lenz's Laws[21]

In the initial instance, a section of the disk is rotating counterclockwise towards the electromagnet with a magnetic field (shown with green arrows in *figure 3*). Following Faraday's law, the magnetic field strength at the disk will increase, and thus the magnetic flux through the disk increases. This causes a current to be induced in the disk which acts as a conductor. Following Lenz's law, the circular induced current must oppose the increase in flux. Therefore, the induced current creates a temporary magnetic field in the opposite direction to that of the electromagnet (shown with an upward blue arrow in *figure 3*). Knowing this, the right-hand rule can be used to show that the current is flowing anticlockwise (shown with red arrows in *figure 3*).

After a period of time, the same section of the disk has passed the centre of the electromagnet and is now rotating away from it. Following Faraday's law, the magnetic field strength at the disk decreases, and thus the magnetic flux through the disk decreases. This results in a current to be induced in the disk. Following Lenz's law, the circular induced current must oppose the decrease in flux. Therefore, the induced current must create a temporary magnetic

[21] Chetvorno (2015, June 13). *Eddy current brake diagram.svg*. Retrieved from: https://en.wikipedia.org/wiki/Eddy_current_brake#/media/File:Eddy_current_brake_diagram.svg. Accessed: 28.08.22

field in the same direction of that of the magnet (shown with a downward blue arrow in *figure 3*). Using the right-hand rule it can be determined that the current is flowing clockwise (shown with red arrows in *figure 3*).

Ultimately, the repulsive and attractive forces between the disk and electromagnet, which are formed by the respective induced currents on the disk, both act to oppose the motion of the disk. The kinetic energy from the rotating disk is transferred to thermal energy within the disk and the disk eventually comes to rest. The thermal energy within the disk eventually dissipates into the surroundings.

Investigation Introduction

This investigation is exploring the effect that the strength of an electromagnet has on the time for a disk to come to rest. To accomplish this, a disk will be rotated such that it reaches a maximum velocity and an electromagnet will be powered. The strength of the electromagnet will be varied by changing the resistance of a rheostat which in turn changes the amount of current the electromagnet receives. The time for the disk to come to rest will be measured. Eddy currents are responsible for the braking effect of the disk.

To establish the effect which eddy currents have on the rotating disk, it is necessary to determine the magnitude of the magnetic flux acting through the disk. Magnetic flux is defined as "a measurement of the total magnetic field which passes through a given area"[22]. This can be represented using the formula $\phi = B \cdot A \cdot cos\theta$ where ϕ is magnetic flux, B is magnetic flux

[22] Khan Academy (2022). *What is magnetic flux?*. Retrieved from: https://www.khanacademy.org/science/physics/magnetic-forces-and-magnetic-fields/magnetic-flux-faradays-law/a/what-is-magnetic-flux. Accessed: 19.10.22

density, A is the area of the surface, and θ is the angle between the magnetic field lines and the normal vector to the surface. This angle is important because a magnetic field line incident on a surface which is not perpendicular to the normal does not receive the full magnetic flux from the field. The area and angle of the surface will be kept constant throughout the investigation; therefore, magnetic flux density is the only significant variable.

Magnetic flux density is defined as the density of magnetic field lines or the number of magnetic field lines passing through a unit area.[23] A formula for this can be derived from Ampere's Circuital Law which states that "the line integral of the magnetic field around a closed path P is proportional to the amount of current that is enclosed by the path"[24]. This can be represented in the integral formula[25] $\oint_P \vec{B} \cdot \vec{dl} = \mu_0 \cdot I_{enc}$ which simplifies to $B = \frac{\mu_0 \cdot N \cdot I}{l}$ where B is magnetic flux density, μ_0 is the permeability of free space which is equal to $4\pi \cdot 10^{-7}\,TmA^{-1}$, N is the number of loops of the solenoid, I is the current through the solenoid, and l is the length of the solenoid.

Therefore, according to the formulas, as the current through the electromagnet increases, the magnetic flux density increases, and thus the magnetic flux increases. There is a proportional relationship between current and magnetic flux.

[23] Poljak, D., Cvetkovic M. (2019). *Magnetic Flux Density*. Retrieved from: https://www.sciencedirect.com/topics/engineering/magnetic-flux-density. Accessed: 20.10.22
[24] Western Kentucky University (2022, February 17). Magnetic Field of a Solenoid. Retrieved from: http://physics.wku.edu/harper/files/apps/pla/examples/04-magnetic-field-solenoid.pdf. Accessed: 20.10.22
[25] The Organic Chemistry Tutor (2017, December 20). *Ampere's Law & Magnetic Field of a Solenoid - Physics & Electromagnetism*. Retrieved from: https://www.youtube.com/watch?v=lLQQjwuqdeg. Accessed: 20.10.22

Hypothesis

The aim of this investigation is to determine how varying the strength of an electromagnet affects the time for an eddy current brake to come to rest. The hypothesis for this investigation is that as the strength of the electromagnet is increased, the time for an eddy current brake to come to rest decreases. The hypothesis is supported by Faraday's and Lenz's Laws, as the strength of the magnetic field increases, the disk will receive more magnetic flux, and the magnitude of the induced currents also increases. Therefore, the magnetic field strength caused by the induced currents will also be greater in order to oppose the stronger electromagnetic fields. This leads to stronger forces opposing the motion of the disk and consequently the time for the disk to come to rest will be shorter. This is further supported when considering the variables in the formulas as discussed in the *Introduction*. Overall, the hypothesis predicts a proportional relationship between the strength of the electromagnet and the time for the disk to come to rest.

However, it should be noted that this hypothesis predicts a general trend for a best case scenario which relies on various assumptions. These assumptions include the absence of air resistance as well as the absence of external forces such as that due to wind from acting on the disk. Another crucial assumption is that the electromagnetic field is homogeneous and the disk is a plane surface.

II. Setup & Methodology

Variables

Independent Variable

Independent variable	Description
Magnetic flux through the disk (± 0.1 mA)	The independent variable in this investigation is the magnetic flux through the disk. This value will be altered by varying the current in the circuit using a rheostat. The current flowing through the circuit will be measured using an ammeter. Eight different values of current will be used in this investigation: 65, 75, 95, 115, 135, 155, 175, and 195 milliamperes. The uncertainty of this measurement is ± 0.1 milliamperes.

Dependent Variable

Dependent variable	Description
Time taken for disk to come to rest (± 0.01 s)	The dependent variable in this investigation is the time taken for the disk to come to rest. The value for time will be measured using a stopwatch. The stopwatch will start once the disk has reached a maximum velocity and once the circuit with the electromagnet is turned on. The stopwatch will stop once the disk has come to a complete rest. The uncertainty of this measurement is ± 0.01 seconds.

Control Variables

Control variable	Value of variable	Why and how variable is controlled
Initial velocity of the disk	The maximum possible velocity the disk can obtain within the time powering the disk circuit	The initial velocity of the disk must be kept constant throughout the investigation as it will directly impact the time taken for the disk to come to rest. If the time is not kept constant the investigation will yield imprecise results. The initial velocity will be kept constant by controlling the time powering the disk circuit.
Time powering the disk circuit	5.0 ± 0.1 s	The time powering the disk circuit must remain constant as it could affect the initial speed of the disk. Although, the time powering the disk should be long enough for the disk to reach a maximum velocity. This time will be measured using a stopwatch.
Potential difference within the disk circuit	3.00 ± 0.01 V	The potential difference within the disk circuit must remain constant. If the potential difference is increased, the initial velocity of the disk will increase. If the potential difference is decreased, the initial velocity of the disk will decrease. The potential difference will be set on the battery eliminator and will not be adjusted throughout the investigation.
Potential difference within the electromagnet circuit	4.00 ± 0.01 V	The potential difference within the electromagnet circuit must remain constant. This is due to

		Ohm's Law which states that potential difference is directly proportional to current. If the potential difference within the circuit is increased, the current within the circuit is also increased which would affect the time for the disk to come to rest. If the potential difference within the circuit is decreased, the current within the circuit is also decreased which would affect the time for the disk to come to rest. The potential difference will be set on the battery eliminator and will not be adjusted throughout the investigation.
Current within the electromagnet circuit between repetitions	Value depends on which trial is being conducted: 65, 75, 95, 115, 135, 155, 175, or 195 ± 0.1 mA	The current within the electromagnetic circuit must be kept constant between repetitions for precise results. If the current is not kept constant it will directly affect the time for the disk to come to rest. The current will be set and varied using a rheostat. Between repetitions, the slider on the rheostat must be kept in place.
Starting distance between disk and electromagnet	0.5 ± 0.1 cm	The starting distance between the disk and the electromagnet must remain constant. If the distance between them is too close, they could bump and interfere with each other which decreases the accuracy of the results. If the distance between them is too far, the electromagnet will not fully affect the disk and the time for the disk to come to rest will be affected. The starting distance between the disk and the electromagnet will be measured and reset before each repetition.

Position of electromagnet relative to disk	Electromagnet should be positioned near the centre of the disk (see *figure 7*)	The position of the electromagnet relative to the disk should be controlled and fixed. Altering the position of the electromagnet during the investigation will lead to inaccurate results. Both the electromagnet and the disk will be fixed in place using clamp stands and clamps.
Material of the disk	Ferrous material (iron/alloys of iron)	The material of the disk must remain constant throughout the investigation. The material must be ferrous as the investigation will take advantage of its magnetic properties.
Radius of disk	7.5 ± 0.1 cm	The radius of the disk must be kept constant during the investigation as changing the radius will affect the time for the disk to come to rest.
Material of the core of the electromagnet	Soft iron core (nail/screw/rod)	The material of the core of the electromagnet must be kept constant throughout the investigation. The core must be soft iron as the electromagnet gains magnetic properties when current flows through the solenoid and loses these properties when current is removed.[26]
Number of loops in the solenoid of the electromagnet	600 ± 1 loops	The number of loops in the solenoid of the electromagnet must remain constant. If the number of loopsis changed it will directly influence the strength of the electromagnet which will affect the time for the disk to come to rest.

[26] Meisel, Jerome (2020, June). *Electromagnet*. Retrieved from: https://www.accessscience.com/content/electromagnet/222100. Accessed: 24.08.22

Diameter and length of the solenoid	Diameter: 10.4 ± 0.1 cm Length: 50.0 ± 0.1 cm	The diameter and length of the solenoid do not directly affect the electromagnetic field, nevertheless they must remain constant throughout the investigation as they could indirectly affect the field. Changing the radius or length of the solenoid would result in changing the number of loops in the solenoid of the electromagnet which will influence the strength of the electromagnet and will consequently affect the time for the disk to come to rest.
Temperature of the electromagnet	Room temperature ≈ 22°C	The temperature of the electromagnet must be kept constant during the investigation. If the temperature increases significantly, the strength of the electromagnetic field will decrease and this will result in a longer time for the disk to come to rest.

Apparatus

Apparatus	Quantity	Use of apparatus
Battery eliminator (output of at least 4.00 ± 0.01 V)	2	The battery eliminators are used as a power source instead of battery to output DC current of different potential differences.
Short wire (minimum length of 50 ± 1 cm)	8	The wires are used to connect components together in the circuits.
Crocodile clip	4	The crocodile clips are used to quickly and cheaply connect wires to stripped wires.
Retort stand	3	The retort stands are stable and are used to fix

		electromagnet and disk in place during the investigation.
Retort clamp	3	The retort clamps connect to retort stands and are used to fix electromagnet and disk in place during the investigation.
Action clamp	1	The action clamp is used to further support and fix the disk in place during the investigation.
Electric DC motor	1	The electric DC motor is used to rotate the disk.
Ferrous disk (radius of 7.5 ± 0.1 cm and thickness of 2.540 ± 0.001 mm)	1	The ferrous disk is rotated and brought to rest with the use of an electromagnet of varying strengths.
Rheostat (280 **Ω**, 1.2 A)	1	The rheostat is used to vary current within the electromagnet circuit.
Ammeter	1	The ammeter measures current in amperes.
Voltmeter	1	The voltmeter measures current in volts.
Soft iron (nail/screw/rod) (length of 50 ± 1 cm)	1	The soft iron is used as a core when building an electromagnet.
Metric ruler (length of 50 ± 1 cm)	1	The ruler will be used to measure the radius of the disk as well as the length and diameter of the electromagnet.
Micrometre (maximum measurement of 25 ± 0.001 mm)	1	The micrometre will be used to measure the diameter of the electromagnet and the thickness of the disk.
Long wire (sufficient length to fully loop around the soft iron core to form a solenoid)	1	This wire is used to create a solenoid by looping it around the soft iron core. The length must remain constant throughout the investigation.
Wire stripper	1	The wire stripper is used to strip wire ends when required (wires on solenoid)
Roll of electrical tape	1	The electrical tape is used to fix the solenoid in place around the soft iron core.
Stopwatch	1	A stopwatch is used to measure the time it takes for the disk to come to rest.

Risk Assessment

Hazard	Risk	Precautions
Contact with live exposed wiring (stripped wires), the electromagnet, faulty plugs or sockets (battery eliminator), and unsafe work practices	Electric shock and burns	Avoid contact with live wires and unnecessary equipment. Cover excess exposed wiring with electrical tape or shorten the exposed portion of the wire by. Only provide power to the electromagnet circuit when required. Before starting the investigation verify the electrical equipment is in good condition and undamaged. Use the recommended voltage with the relevant equipment. Do not expose the wires to liquids - avoid drinks near the investigation setup.
	Electrocution	
Faulty electrical equipment, wiring, plugs, or sockets	Arc flashes and blasts (high-power sparks)	Before starting the investigation verify the electrical equipment and wiring is in good condition and undamaged. Ensure flammable materials, such as clothing, are a safe distance from equipment and live wires. Ensure a class C fire extinguisher is readily available in the event of electrical fires.
	Fires and explosions	
Disk rotating at high speeds, and disk detaching from motor	Injuries such as cuts or lacerations	Ensure the disk is properly secured to the motor. Avoid contact with the rotating disk.
Magnetic materials near electromagnet		Ensure magnetic materials (metals) are a safe distance away from the electromagnet. Only provide power to the electromagnet circuit when required. Use the recommended voltage within the electromagnet circuit.

Electrical risks, hazards, and precautions are adapted from suggestions by the British government supported Health and Safety Executive[27]

[27] Health and Safety Executive (2022, July 5). *Electrical safety*. Retrieved from: https://www.hse.gov.uk/toolbox/electrical.htm. Accessed: 25.08.22

In addition to assessing the risks of potential hazards, it is also important to consider the ethical and environmental concerns.

Ethical considerations involve the exposure of humans to electromagnetic fields and their radiation. As stated by the World Health Organisation, "with more and more research data available, it has become increasingly unlikely that exposure to electromagnetic fields constitutes a serious health hazard." Regardless, the strength of the electromagnetic fields in this investigation are not high enough to cause concern. Although, it should be noted that prolonged exposure to this radiation is not recommended and should be avoided.

Environmental considerations are not applicable as the investigation is to be conducted in a closed environment.

Method

In this section a step-by-step procedure will thoroughly describe how the investigation will be carried out.

Equipment setup

1. Prepare all the necessary equipment required for the investigation.
2. Complete a thorough assessment of the equipment checking for damage or other visible faults. This is a precaution to ensure all equipment is safe and to limit the amount of possible risks.
3. Attach the ferrous disk onto the shaft of the electric motor. The disk must be secure to prevent the risks in *hazard 5: disk detaching from motor*. For reference, see *figure 4*.

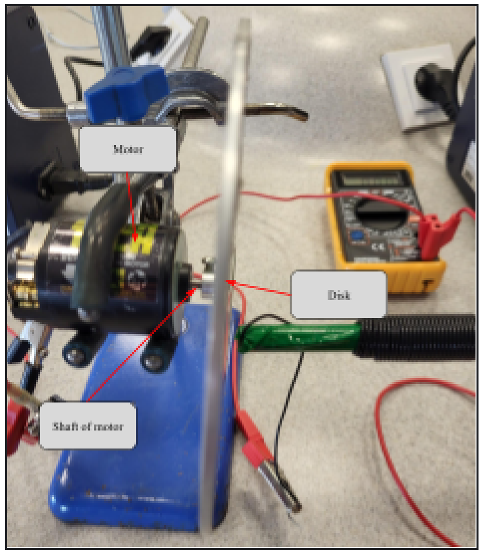


figure 4: Attachment of disk onto motor

4. Build the electromagnet. This will require the soft iron rod, the long wire, electrical tape, and the wire strippers. The soft iron will act as the core of the electromagnet. Starting at one end, tightly loop the wire around the iron core in a regular configuration until the core is completely covered; this will yield a solenoid. During this process, record the total number of loops of the solenoid. Using electrical tape, tape the ends of the solenoid securely onto the iron core, the ends of the solenoid must be protruding. Using wire strippers, strip the ends of the solenoid. For reference, see *figure 5*.

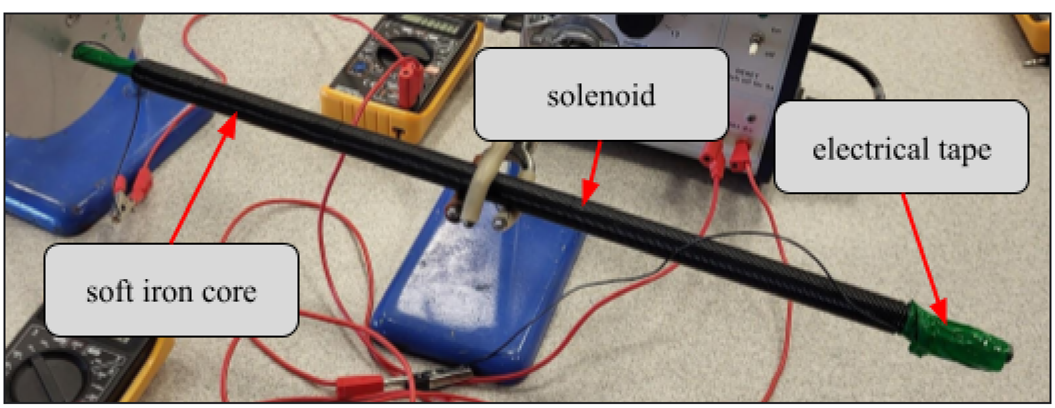


figure 5: Electromagnet with solenoid

5. Construct the first circuit (disk circuit) following the circuit diagram provided in *figure 6*. This will require two short wires, two crocodile clips (to connect wires to the wires on the motor), one battery eliminator (power source), and the disk attached to the motor.

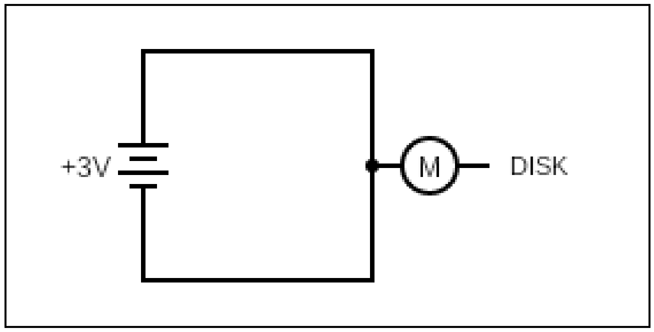


figure 6: Circuit diagram 1 - disk circuit

6. Test the first circuit. Plug in the battery eliminator, set it to a voltage of 3 volts, and turn on the battery eliminator. The circuit is working successfully if the disk begins to rotate.
7. Construct the second circuit (electromagnet circuit) following the circuit diagram provided in *figure 7*. This will require 6 short wires, 2 crocodile clips (to connect wires to the solenoid), one battery eliminator (power source), the rheostat, the ammeter, and the voltmeter.

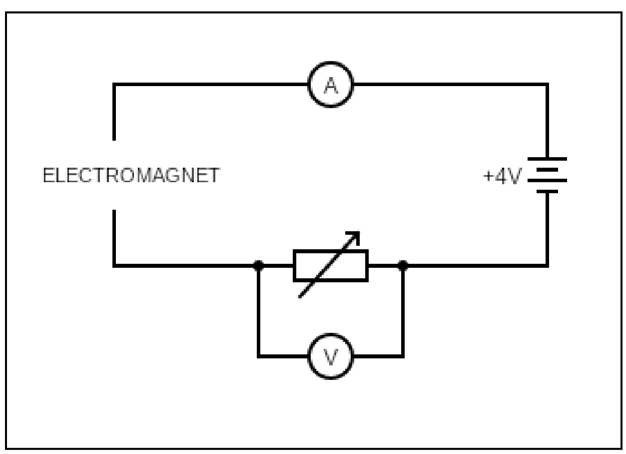


figure 7: Circuit diagram 2 - electromagnet circuit

8. Test the second circuit. Plug in the battery eliminator, set it to a voltage of 4 volts, and turn on the battery eliminator. The circuit is working successfully, if the readings on the ammeter vary when the slider on the rheostat is adjusted.
9. Fix the position of the disk and electromagnet above the desk using retort stands and retort clamps such that the disk will not interfere with the desk. Position the disk and electromagnet a distance of precisely 0.5 centimetres apart from each other. Further secure the position of the retort stand holding the disk with an action clamp. For reference, see *figure 8*.

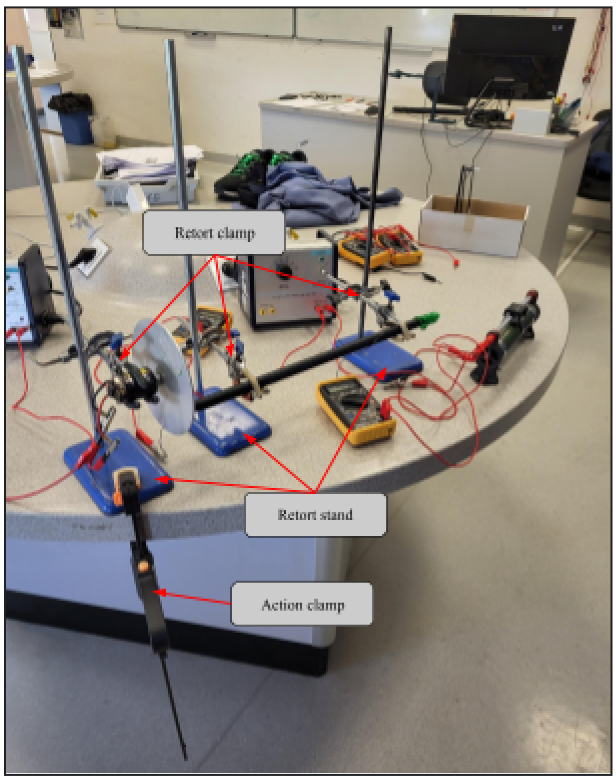


figure 8: Fixed position of disk and electromagnet

10. The complete circuit and investigation setup can be seen and referred to in *figures 9* and *10* respectively.

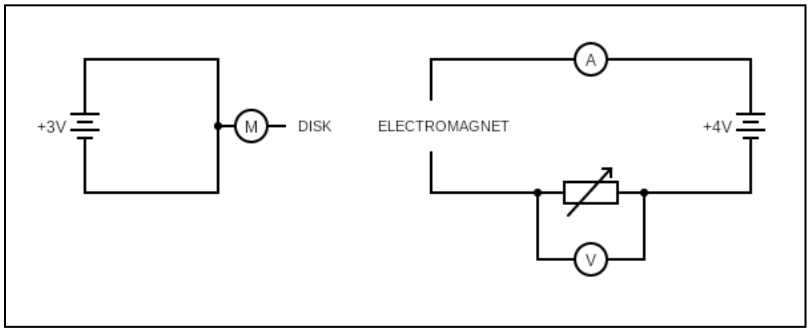


figure 9: Complete circuit diagram

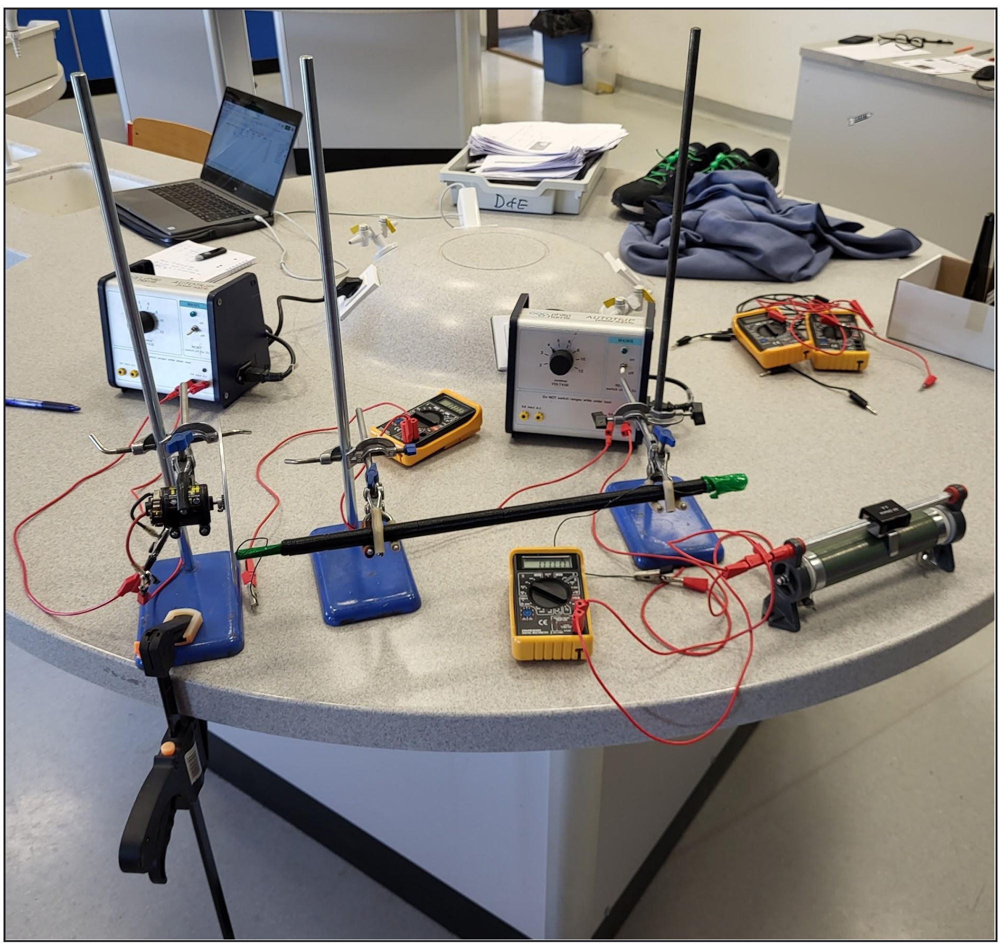


figure 10: Complete investigation setup

Data Collection and Processing

1. Firstly, record measurements of the equipment which will be required later when performing calculations:
    a. Measure and record the radius of the disk using a ruler.
    b. Measure and record the length of the electromagnet using a ruler.
    c. Measureand record the diameter of the electromagnet using a micrometre.
2. Before the investigation can begin a control trial must be completed:
    a. Start the stopwatch and power the disk circuit by turning on the battery eliminator at 3 volts.
    b. After exactly 5 seconds, power off the disk circuit by turning off the battery eliminator.
    c. Immediately restart the stopwatch.
    d. Wait for the disk to come to a complete rest, once it does stop the stopwatch.
    e. Record the reading on the stopwatch and repeat this process from step 2.a. four more times.
3. Power the electromagnet circuit to 4 volts, adjust the slider on the rheostat until the ammeter is displaying a current of 65 milliamperes, then power off the electromagnet circuit.
4. Start the stopwatch and power the disk circuit to 3 volts.
5. After exactly 5 seconds, power off the disk circuit.
6. Immediately restart the stopwatch and power the electromagnet circuit to 4 volts.
7. Stop the stopwatch once the disk comes to a complete rest.

8. Record the reading on the stopwatch.
9. Repeat steps 3-8 five times with the same current to reduce random errors and to increase the precision of the collected data.
10. Repeat steps 3-9 using different currents: 75, 95, 115, 135, 155, 175, and 195 milliamperes.
11. Calculate the mean time for the disk to come to rest.
12. Calculate the magnetic flux density of the electromagnet, B, using the relevant formula outlined in the *Background Information*.
13. Calculate the magnetic flux through the disk, ϕ, using the relevant formula outlined in the *Background Information*.
14. Calculate the percentage uncertainties present within the data.
15. Plot the graph of mean time for the disk to come to rest against the magnetic flux through the disk with a line of best fit, error bars, and a line of worst fit.

III. Experimental Analysis

Raw Data

In this section data which has been collected following the procedure in the *Method* is presented.

Raw data table 1: Voltage of circuit rotating disk before trial

Voltage, V (± 0.01 V)
3.00

Raw data table 2: Time rotating disk before trial

Time, t (± 0.01 s)
5.00

Raw data table 3: Distance between disk and electromagnet

Distance, d (± 0.1 cm)
0.5

Raw data table 4: Measurements of disk

Mass, m (± 1 g)	Radius, r (± 0.10 cm)	Thickness, w (± 0.001 mm)
5120	7.50	2.540

Raw data table 4: Measurements of electromagnet (and solenoid)

Number of loops, N (± 1)	Length, l (± 0.1 cm)	Diameter, d (± 0.01 mm)
600	50.0	10.40

Raw data table 5: Measurements collected during trials (V and I of electromagnet circuit)

Voltage, V (± 0.01 V)	**Current, I (± 0.1 mA)**	**Time for disk to come to rest, t (± 0.01 s)**					
		Repeat 1	Repeat 2	Repeat 3	Repeat 4	Repeat 5	Mean
0.00	0.0	34.83	35.18	34.62	35.41	34.94	35.00
3.52	65.7	32.56	32.42	33.34	33.07	32.96	32.87
3.46	74.8	30.93	31.80	32.11	32.32	31.75	31.78
3.26	94.2	28.72	27.84	28.43	27.54	28.33	28.17
3.09	117.2	23.73	24.52	24.16	23.83	24.34	24.12
2.96	135.7	19.54	20.32	19.81	19.30	19.05	19.60
2.80	155.8	15.97	15.41	14.58	15.71	14.84	15.30
2.68	177.2	13.74	13.34	14.01	13.49	13.56	13.63
2.54	196.5	11.26	10.43	10.73	11.02	11.75	11.04

Processed Data

In this section data is processed following the procedure in the *Method*. Example calculations for the second row of the data tables are provided for further understanding on how the values were acquired.

Processed data table: Mean time, Magnetic flux density, and magnetic flux

Current, I (± 0.1 mA)	**Mean time, t (± 0.01 s)**	**Magnetic flux density, B ($\cdot 10^{-5}$ T)**	**Magnetic flux, ϕ ($\cdot 10^{-7}$ Wb)**
0.0	35.00	0.00	0.00
65.7	32.87	9.91	17.5
74.8	31.78	11.3	19.9
94.2	28.17	14.2	25.1
117.2	24.12	17.7	31.2
135.7	19.60	20.5	36.2
155.8	15.30	23.5	41.5
177.2	13.63	26.7	47.2
196.5	11.04	29.6	52.4

Example calculation - Mean time for disk to come to rest:

$$\bar{x} = \frac{\Sigma x}{n}$$

$$\bar{x} = \frac{32.56+32.42+33.34+33.07+32.96}{5}$$

$$\bar{x} = \frac{164.35}{5}$$

$$\bar{x} = 32.87\ s$$

Example calculation - Magnetic flux density of the electromagnet:

$$B = \frac{\mu_0 \cdot N \cdot I}{l}$$

$$B = \frac{(4 \cdot \pi \cdot 10^{-7}) \cdot 600 \cdot 65.7 \cdot 10^{-3}}{50.0 \cdot 10^{-2}}$$

$$B = 9.907326592 \cdot 10^{-5}\, T$$

$$B \approx 9.91 \cdot 10^{-5}\, T$$

Example calculation - Magnetic flux through the disk:

$$\phi = B \cdot A \cdot cos\theta$$

$$\phi = B \cdot \pi \cdot r^2 \cdot cos\theta$$

$$\phi = (9.91 \cdot 10^{-5}) \cdot \pi \cdot 0.0750^2 \cdot cos(0)$$

$$\phi = 1.751241555 \cdot 10^{-6}\, Wb$$

$$\phi \approx 17.5 \cdot 10^{-7}\, Wb$$

Treatment of Uncertainties

In this section uncertainties are calculated. Example calculations for the second row of the data tables are provided for further understanding on how the values were acquired.

Uncertainty table 1: Mean time uncertainties

Time, t (± 0.01 s)		**Mean time percentage uncertainty (%)**
Mean	Range	
35.00	0.79	1.13
32.87	0.92	1.40
31.78	1.39	2.19
28.17	1.18	2.09
24.12	0.79	1.64
19.60	1.27	3.24
15.30	1.39	4.54
13.63	0.67	2.46
11.04	1.32	5.98

Example calculation - Percentage uncertainty of mean time for disk to come to rest:

$$range = max\ value - min\ value$$

$$range = 33.34 - 32.42$$

$$range = 0.92$$

$$\%\ Unc. = \frac{1}{2} \cdot \frac{range}{mean} \cdot 100\%$$

$$\%\ Unc.(t) = \frac{1}{2} \cdot \frac{0.92}{32.87} \cdot 100\%$$

$$\%\ Unc.(t) = 1.399452388\ \%$$

$$\% \, Unc.(t) \approx 1.40 \,\%$$

Uncertainty table 2: Current, magnetic flux density, and magnetic flux uncertainties

Current, I (± 0.1 mA)	**Current percentage uncertainty (%)**	**Magnetic flux density, B ($\cdot$ 10^{-5} T)**	**Mag. flux density percentage uncertainty (%)**	**Mag. flux, ϕ ($\cdot$ 10^{-7} Wb)**	**Mag. flux percentage uncertainty (%)**
0.0	0.00	0.00	0.367	0.00	3.03
65.7	0.152	9.91	0.519	17.5	3.19
74.8	0.134	11.3	0.500	19.9	3.17
94.2	0.106	14.2	0.473	25.1	3.14
117.2	0.0853	17.7	0.452	31.2	3.12
135.7	0.0737	20.5	0.440	36.2	3.11
155.8	0.0642	23.5	0.431	41.5	3.10
177.2	0.0564	26.7	0.423	47.2	3.09
196.5	0.0509	29.6	0.418	52.4	3.08

Example calculation - Percentage uncertainty of current in electromagnet circuit:

$$\% \, Unc. = \frac{absolute\ uncertainty}{value} \cdot 100\%$$

$$\% \, Unc.(I) = \frac{0.1}{65.7} \cdot 10^{-3} \cdot 100\%$$

$$\% \, Unc.(I) = 0.1522070015 \,\%$$

$$\% \, Unc.(I) \approx 0.152 \,\%$$

Example calculation - Percentage uncertainty of magnetic flux density of electromagnet:

$$\% \, Unc.(B) = \% \, Unc.(N) + \% \, Unc.(I) + \% \, Unc.(l)$$

$$\% \, Unc. = \frac{absolute\ uncertainty}{value} \cdot 100\%$$

$$\% \, Unc.(N) = \frac{1}{600} \cdot 100\%$$

$$\% \, Unc.(N) = 0.1\overline{6}\,\%$$

$$\% \, Unc.(l) = \frac{0.1}{50.0} \cdot 100\%$$

$$\% \, Unc.(l) = 0.2\,\%$$

$$\% \, Unc.(B) = 0.1\overline{6}\% + 0.152\% + 0.2\%$$

$$\% \, Unc.(B) \approx 0.519\,\%$$

Example calculation - Percentage uncertainty of magnetic flux through the disk:

$$\% \, Unc.(\phi) = \% \, Unc.(B) + 2 \cdot \% \, Unc.(r)$$

$$\% \, Unc. = \frac{absolute\ uncertainty}{value} \cdot 100\%$$

$$\% \, Unc.(r) = \frac{0.10}{7.50} \cdot 100\%$$

$$\% \, Unc.(r) = 1.\overline{3}\,\%$$

$$\% \, Unc.(\phi) = 0.519\% + 2 \cdot 1.\overline{3}\%$$

$$\% \, Unc.(\phi) \approx 3.19\,\%$$

Graphed Data

figure 11: A graph to show the relationship between magnetic flux through the disk and time for the disk to come to rest (including control trial)

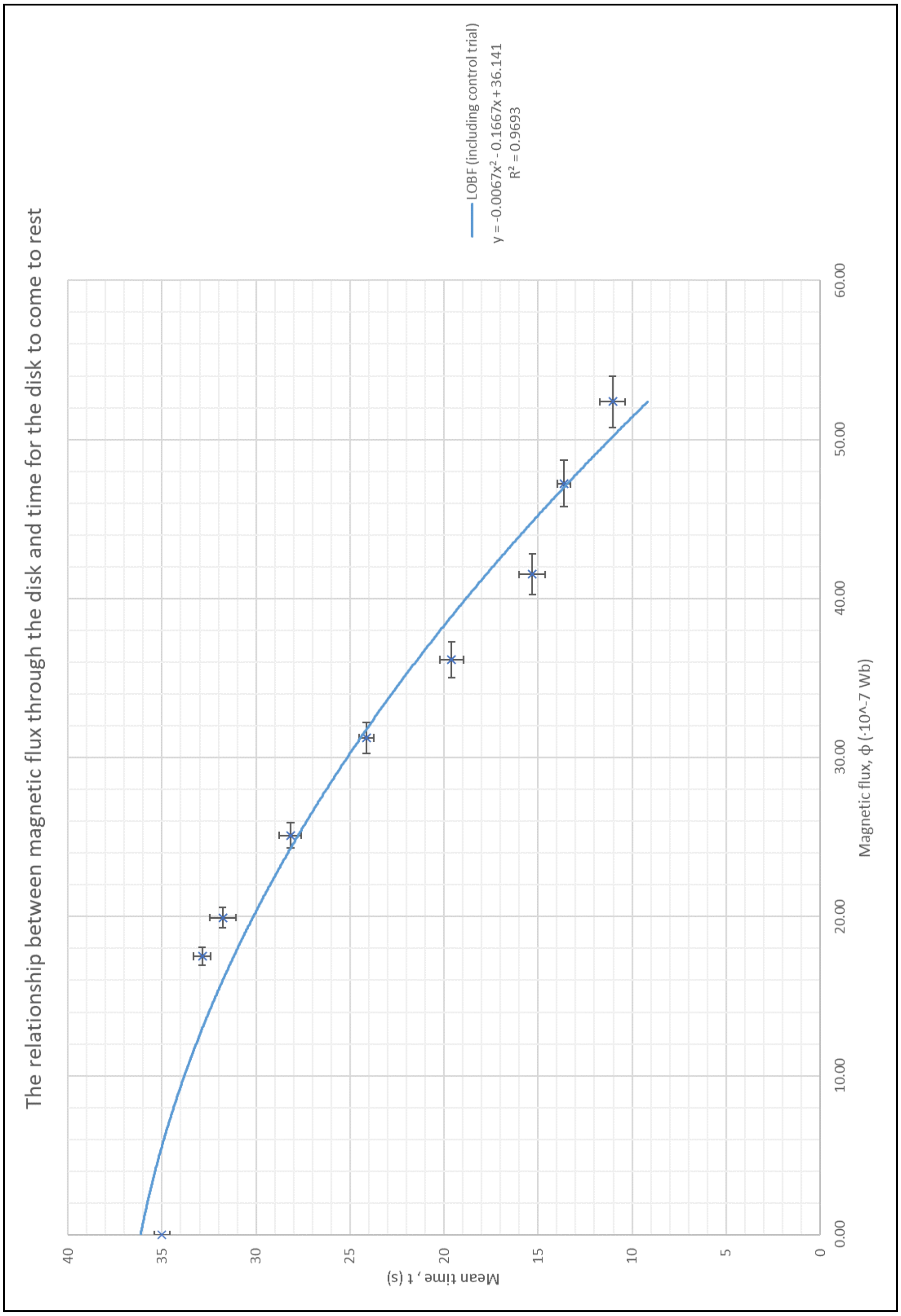
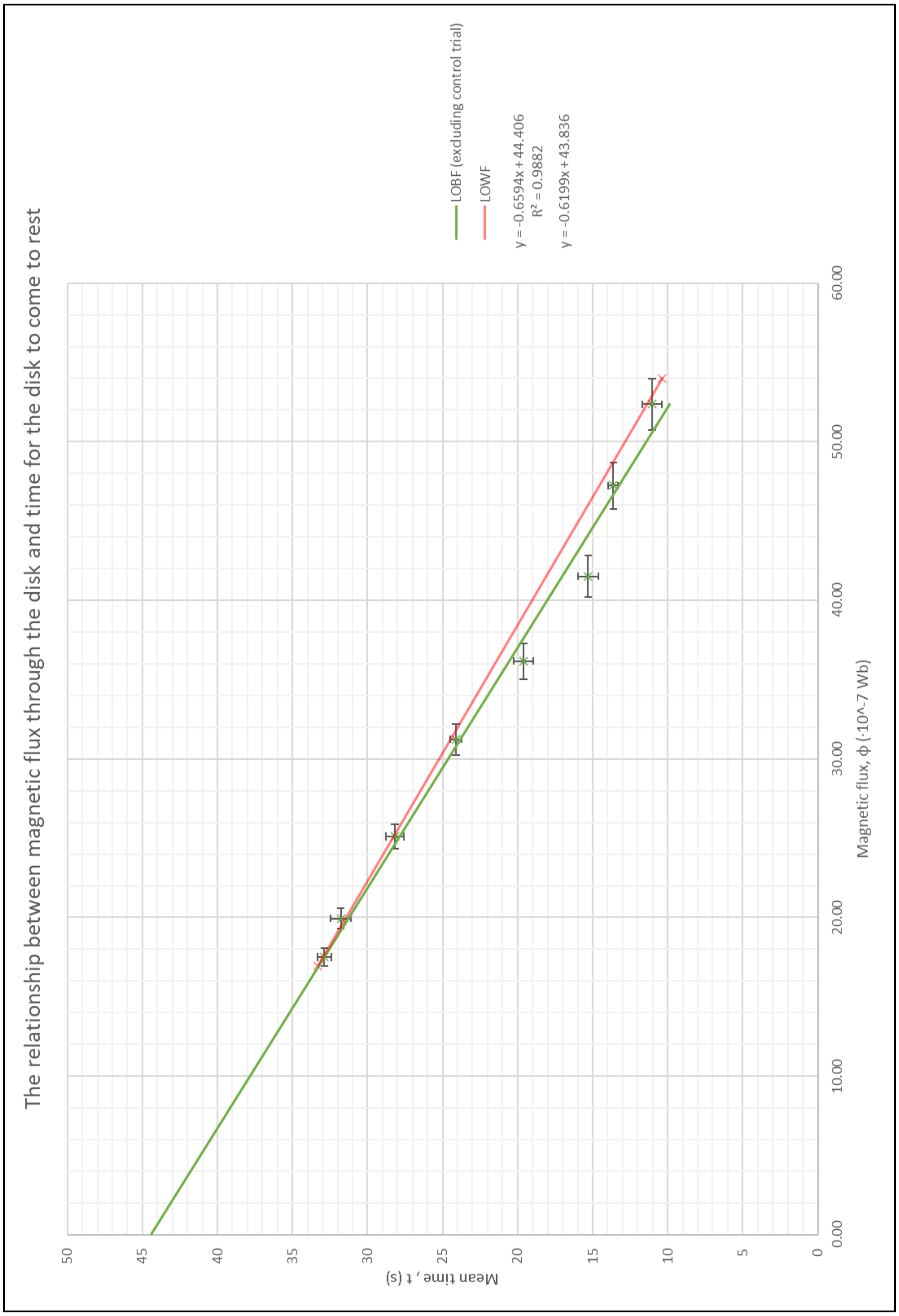


figure 12: A graph to show the relationship between magnetic flux through the disk and time for the disk to come to rest (excluding control trial)



Analysis

Both graphs plotted the mean time for the disk to come to rest against the magnetic flux through the disk. In the first graph, *figure 11*, the control trial was included which consequently resulted in a curved line of best fit with the polynomial equation of $y = -0.0067x^2 - 0.1667x + 36.141$. In the second graph, *figure 12*, the control trial was excluded and this resulted in a linear line of best fit with the equation of $y = -0.6594x + 44.406$. Both graphs have a negative gradient as seen in their equations. A negative gradient indicates a negative correlation between the variables. In other words, as the magnetic flux through the disk increases, the time for the disk to come to rest decreases.

Considering the general trend in *figure 12* is linear, it can be established that time is directly proportional to negative magnetic flux. In this proportional relationship where $t \propto -\phi$, a constant of proportionality can be calculated so that $t \propto k \cdot \phi$, where k is the constant of proportionality. In linear functions the constant of proportionality is equal to the gradient.[28] Therefore, in this case, the constant of proportionality, k is equal to -0.6594 so that $t \propto -0.6594\phi$.

To determine the reliability of this proportional relationship, the percentage uncertainty of the gradient must be calculated. For this reason, the steepest line of worst fit with the linear equation of $y = -0.6199x + 43.836$ is plotted in red in *figure 12*. The percentage uncertainty of the gradient can be calculated as follows:

[28] Michigan State University (2022). Glossary: Constant of proportionality. Retrieved from: https://connectedmath.msu.edu/families/glossary/. Accessed: 13.11.22

$$\% \, Unc.(m) = \frac{m(LOBF) - m(LOWF)}{m(LOBF)} * 100\%$$

$$\% \, Unc.(m) = \frac{-0.6594 - (-0.6199)}{-0.6594} * 100\%$$

$$\% \, Unc.(m) = 5.990294207 \, \%$$

$$\% \, Unc.(m) \approx 5.99 \, \%$$

Another method to determine the reliability of the proportional relationship is using the coefficient of determination (R^2), which is "a measure that assesses the ability of a model to predict an outcome in the linear regression."[29] In *figure 12*, the coefficient of determination is equal to 0.9882.

Conclusion

The aim of this investigation is to determine how varying strengths of an electromagnet affect the time for an eddy current brake to come to rest. As calculated in the *Analysis*, the constant of proportionality between time and magnetic flux is equal to -0.6594. The negative relationship indicates that as magnetic flux increases, time decreases. Following Faraday's and Lenz's Laws, an increase in magnetic flux induces a current with a greater magnitude which in turn creates a stronger magnetic field. This stronger magnetic field acts to oppose the electromagnetic field which must also be stronger to account for the increase in magnetic flux. The stronger fields cause a stronger force to oppose the motion of the disk. Therefore, as the strength of an electromagnet is increased, the time for an eddy current brake to come to rest decreases.

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[29] Britannica (2022, October 4). coefficient of determination. Retrieved from: https://www.britannica.com/science/coefficient-of-determination. Accessed: 13.11.22

The hypothesis for this investigation predicted a proportional relationship between the strength of the electromagnet and the time for the disk to come to rest where as the strength is increased, the time is decreased. As explained above, this relationship holds and thus the hypothesis is accepted.

IV. Furtherance

Evaluation

To effectively evaluate the investigation, strengths and weaknesses in the method must be identified, assessed, and improved.

A significant strength within the investigation is the low uncertainty values throughout the measurements which lead to an overall uncertainty on the line of best fit of only 5.99 %. Low uncertainty values indicate precise results and the absence of many systematic errors. They also give direct feedback on the choice of equipment used to measure readings. In this case, low uncertainties verify that the appropriate equipment was chosen. A prime example of this is the measurements for time. The low uncertainty values of time can be visualised on the graph within the magnitude of the vertical error bars. The mode uncertainty of time was approximately 2 %, this low uncertainty can be attributed to the stopwatch which had an absolute uncertainty of ± 0.01 seconds. However, the highest uncertainty for time was 5.98 %. The reason for the higher value is that there was greater range in values of the repeat measurements caused by random error. To eliminate this error and further reduce the uncertainty, light gates should be implemented across the disk.

The other significant uncertainty present within the investigation is the uncertainty for the magnetic flux which can be visualised in the graph with the horizontal error bars. The mode calculated uncertainty for the magnetic flux was approximately 3 %. The main factor contributing to this value is the uncertainty for the area and consequently the radius of the disk ($2 \cdot 1.\overline{3}$ %). To reduce this uncertainty, the radius should be recorded with more precise equipment such as a micrometre instead of a ruler. Although the 3 % uncertainty is relatively low, there are a number of weaknesses in the method of the investigation which cause systematic errors that are not accounted for within the uncertainty. For example, the current in the circuit, as displayed on the ammeter, was constantly fluctuating. This is due to either an inconsistent resistance caused by the rheostat or by the poor quality of the wires. To eliminate the error of an inconsistent resistance, metal wireround resistors should be implemented instead of a rheostat. Wireround resistors offer the highest precision when compared to other resistors.[30] To increase the resistance and vary the current, the resistor can be interchanged for a resistor of higher resistance or additional resistors can be added in series. Furthermore, to eliminate the systematic error caused by the poor quality of the wires, new wires that are properly insulated should be implemented to completely remove any loss of current.

Another strength in the investigation is the value for the coefficient of determination which is 0.9882. This value is very high and falls within the accepted range where a maximum value of 1 indicates that the line of best fit perfectly fits the data.[31] Therefore, the line of best fit that represents the relationship between time and magnetic flux is reliable.

An additional weakness in the investigation that is not accounted for in the uncertainties is that the distance between the electromagnet and disk was not kept constant throughout the trial. During the trial, the disk began to shake due to its high speeds, which caused it to move horizontally towards the electromagnet. This systematic error did not have a large impact, however, it still affected the results directly by causing the disk to come to rest faster. To

[30] Hovsepian, F. (2021, May 24). Metal Foil Resistors. Retrieved from: https://riedon.com/blog/metal-foil-resistors/. Accessed: 13.11.22

[31] Britannica (2022, October 4). coefficient of determination. Retrieved from: https://www.britannica.com/science/coefficient-of-determination. Accessed: 13.11.22

completely remove this error, the disk must be firmly held in place with action clamps. An alternative solution is to reduce the maximum speed at which the disk is spinning throughout the investigation by switching on the disk circuit for a shorter amount of time.

Overall, the investigation yielded precise and accurate results as verified by the low uncertainty for the line of best fit of 5.99 % as well as by the value of the coefficient of determination of 0.9882. With the implementation of the suggested improvements, the results of the investigation will be further bolstered.

Further Discussion

The real world application of the concept explored in this investigation is eddy current braking systems where pressing the brake pedal would essentially act as moving the rheostat slider to decrease resistance and increase current within the circuit. As determined within the investigation, this will cause the wheel to decelerate and stop the vehicle. Therefore, on a larger scale the concept is proven to hold and as eddy current braking systems tend to last longer than friction braking systems, they are a viable option for the future.

Further research to be conducted includes the effect of temperature on eddy current braking, and determining any limitations on applying eddy current brakes on a larger scale.

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