International Baccalaureate:

Extended essay - Rate of change of magnetic flux

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Subject – Physics

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Table of Contents

1 Introduction:

1.1 Overview

Classical electromagnetism is a field where electromagnetic force is studied on a macro scale and is one of the fundamental forces. The essay investigates electromagnetic induction when there is a moving magnetic field relative to a conductive wire.

A changing magnetic field induces a current in a conducting wire [Faraday's law of induction] and this essay aims to explore the relationship between the rate of change of magnetic field lines and induced EMF. Electromagnetism is used everywhere; the whole world is based on it and yet is poorly understood by all including me. It's mysterious why magnetic fields induce electric fields or vice a versa, it was globally accepted that when a charge moved it created magnetism.

1.2 Research Question

Electromagnetic induction depends on several factors which are controlled when investigating the effects of one. Since electronic equipment are used, multiple precautions are taken to control the confounding variables to increase accuracy. The independent variable is the rate of change of magnetic flux, the dependent variable is the EMF induced and all the other variables affecting DV are controlled.

Thus the research question emerges:

How does varying the rate of change of magnetic flux density affect the EMF induced in a coil of metal wire, when the dimensions of the magnet, the angle between the coil and the motion of the magnet, temperature of the system, dimensions of the wire and dimensions of the coil are controlled?

1.3 Background information

When a magnet moves relative to a conductive coil, Faraday devised a formula that calculated how much EMF was induced in the coil. The direction of the current induced in the conductor is governed by Lenz's law[1]. The formula:

$$\text{EMF} = -N\,\frac{\Delta\Phi}{\Delta t} \qquad (1)$$

Where $\Phi = BA\cos\theta$,

B=magnetic field strength

A=surface area of the coil

θ=angle between the magnetic field vector and normal of the surface.

Formula (1) tells that the EMF induced is directly proportional to $\Delta\phi/\Delta t$[2] and the number of turns in a coil. This essay studies the effect of oscillating $\Delta\phi/\Delta t$ on EMF induced.

For an oscillating magnet, the graph of position against time follows a sinusoidal or co-sinusoidal graph depending on the initial position (fixed point). Magnetic flux density is dependent on the distance between the magnet and the position from which the magnetic field strength is calculated; therefore magnetic flux density against time also follows a sinusoidal wave. The $\Delta\phi/\Delta t$ vs time will also be a sinusoidal graph which will passes through zero since the magnet stops to change velocity at the peak positions.

1 "The direction of the current is such that the magnetic field that it creates opposes the initial changing magnetic field that induced the current".

2 Rate of change of magnetic flux.

2 Experimental setup

2.1 Variables

Variable	Type	Why/How is it controlled?	Uncertainty
$\Delta\phi/\Delta t$	Independent	By PWM circuit that varies the power input of the system, varying the number of rotations per minute of motor.	$\pm$0.01s
EMF induced	dependent	By connecting a multi meter in parallel connection to the coil. [AC voltage mode]	$\pm$0.001V
Room temperature	controlled	Resistance of the wire used and the magnetic field strength of magnet used are temperature dependent so temperature of the room is controlled.	$\pm$0.5K
dimensions of the coil	controlled	Magnetic flux density is dependent on the surface area through which the field lines are passing, so important to control the cross-sectional area of the coil. The length and the cross-sectional area of the wire used determine the resistance of the coil.	$\pm$0.00001m uncertainty propagated accordingly for area.
Dimensions of the magnet	controlled	Magnetic field strength depends on the material and the dimensions of the magnet, as a result these factors are controlled.	$\pm$0.00001m
Orientation of the magnets to the coil	controlled	Magnetic flux density depends on the angle between the motion of the magnets and the normal to surface through which the magnet is	$\pm$0.5°

		passing.	

Table 2.1.1

2.2 Planning the setup

In this EE, an oscillating motion of a magnetic field going through a coil of metal wire is set up. The magnetic fields were created through neodymium magnets. Calculating the strength of the magnetic field requires a magnetometer, [difficult to procure], so the below formula used:

$$B = \frac{B_r}{2}\left(\frac{D+z}{\sqrt{R^2+(D+z)^2}} - \frac{z}{\sqrt{R^2+z^2}}\right)$$

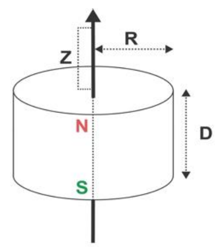

Figure 2.2.1

Where Br=Remanence field, which is 1.2 for neodymium magnets;

D=magnet thickness,

z=distance from the pole face on the symmetrical axis

R=radius of the pole face.

The oscillator allowed the magnet to have a back-and-forth range of motion and it is necessary that it had no vertical movement otherwise the magnet would create friction with coil. Final design was set using the circular motion of a spinning disc and a long shaft to create the desired motion range. Spinning disc attached to the shaft is connected to magnet ensuring that the joint between the magnet and shaft is flexible. Since Δϕ/Δt was varied and calculated, a steady rate is crucial, which was achieved by a DC motor; but to vary the RPM of that motor power supplied needs to vary, so a pulse width modulation (PWM) circuit was used which varied the voltage and power by turning the signal on and off rapidly. To decrease friction between the disc and shaft a ball bearing is attached on the disc. For Stability, the motor was attached to a wooden board using a C-clamp.

As Oscillator design was confirmed, designing the next part of the system started, the coil. A coated insulated copper wire was selected, if not insulated the current will take the shortest path and no noticeable EMF will be induced. A non-ferromagnetic shaft was connected to the magnet, ensuring that the shaft does not get attracted to the magnet and interfere with the motion. The joint connecting both, was a simple loop of wire connected to the magnet with the help of an adhesive.

2.3 Optimization Points

- Conduct the experiment in a closed and cold environment to reduce resistance of the coil.
- No other conductive surface should touch coil, or probes used for measuring.

2.4 Safety measures

- Wearing insulated gloves.
- Caution while using Strong adhesives.
- Strong neodymium magnets used. Need to wear thick gloves to avoid skin pinching.

3 Designing and procedure

3.1 Initial attempt and improvements

When building the experimental setup, I encountered many obstacles which could possibly affect the data collected. One difficulty that I faced was the selection of an adequate motor, a normal 4-to-12-volt DC motor was used to rotate the disc, it was able to spin the disc but not at high speeds to generate noticeable voltage. Then, a heavy duty 12-to-24-volts DC motor was used which was significantly larger and stronger. After trying this larger motor, it was apparent that this model was able to rotate the disc at extremely high velocities and displayed an extensive range of speeds. Since it needed more than 12 volts, an AC to DC converter was used to utilize power from wall outlets. At first I inserted all the magnets in the system which decreased the motor's rotational speed motor because 20 magnets were heavy, as a solution I decreased the number of magnets to 7 which allowed the motor to function at full speed while providing maximum magnetic field strength.

Furthermore, I decided to use an insulted 18-gauge copper wire with exactly 60 turns and length 9cm. This design for the coil did not work efficiently and yielded non readable voltage. This was not apparent at first but soon I realized that number of turns was a bigger factor than cross section of the wire when determining the voltage induced, also the portion receiving the maximum $\Delta\phi/\Delta t$ for the 18-gauge wire had a very low coil density (number of coils per meter) which was a reason limiting the voltage produced. So, I redesigned my coil with more turns and decreased the CS[3] of the wire which allowed stacking of the coils, I could increase the coil density by decreasing the length of the coil. Finally, an insulted

[3] Cross-sectional area

copper wire with a diameter of 0.2mm was selected; this allowed 200 turns in 26.5mm length.

As the wire is thin the coil easily deformed under stress, to add strength to its structure a PVC pipe was used to wrap the coil. The addition of a pipe added distance between the magnets and the coil decreasing the magnetic field strength as it follows the inverse square law. To avoid this, I sanded down the pipe from 3.10mm to 2.65mm in thickness.

As EMF induced was so minute and did not exceed a voltage of 1.5V, it was difficult to record significant data with adequate accuracy. I initially used DT830D digital multi meter which had two modes to calculate AC voltage – 750V and 200V, the 250V had an uncertainty of ±0.1V which was not accurate. Then I used ‘scientific auto range DMM SM 7022’ which had an auto mode for AC voltage and provided an accuracy of ±0.001V. Such low uncertainty was a significant improvement from the earlier multimeter and yielded more diverse data.

The stopwatch was changed as it was not able to display all the milliseconds and was skipping 10 to 20ms which would make the data inaccurate. This was partially due to lack of sufficient refresh rate; therefore, my laptop was used with a higher refresh rate, it still skipped 3 to 4ms.

3.2 Apparatus and materials used

1. Plank-thickness=3mm
2. Cylindrical neodymium magnets-length=3mm, radius=7.5mm
3. Copper wire-radius=0.15mm
4. PVC pipe-inner/Outer radius=7.85/10.35mm
5. Ball bearing-radius=5mm
6. Metallic and plastic C clamps
7. PWM circuit
8. Electrical Wires
9. Scientific auto range DMM SM7022
10. AC to DC convertor
11. Digital Stopwatch
12. Sandpaper
13. Cello-tape and adhesive
14. Nails
15. 18-gauge brass wire
16. Thermometer
17. Slow-motion camera
18. Metal disc-radius=25mm

3.3 Model construction

1. Standard wooden plank of three centimeters thick as base for the whole model.
2. Hole drilled to the metal disk, the hole should match the radius of the motor's axle. Disc attached to the motor using an adhesive.
3. Bearing attached to the disc using adhesive.
4. Shaft made out of a twisted 18-gauge brass wire of appropriate length and connected to one of the ball bearings on the disc. The same wire used to make a loop of wire which acts as the handle connecting the magnets to the shaft, attach about 7 magnets to the handle.
5. Copper wire wrapped around the pipe 200 times.
6. Wrap cello-tape around the coil to insulate the coil from external stimuli.
7. Attach the motor to a PWM circuit and the circuit to an AC/DC converter.
8. Insert the magnets into the pipe.
9. Using a C clamp of the appropriate size attach the motor to the wooden base.
10. A spare piece of wood used to elevate the coil to the same height as the center of disc. Locate the appropriate position of the coil and place the spare wood piece between the pipe and the wooden base, nail the wooden piece to the base and attach the coil to the wood piece using a C clamp.
11. Insulation removed from the ends of the coil using a sharp tool and attachedto the multimeter.
12. Stopwatch placed near the motor and set the slow-motion camera such that it captures the moving disc, multimeter, and the stopwatch.

3.4 Experimental setup

The final model:

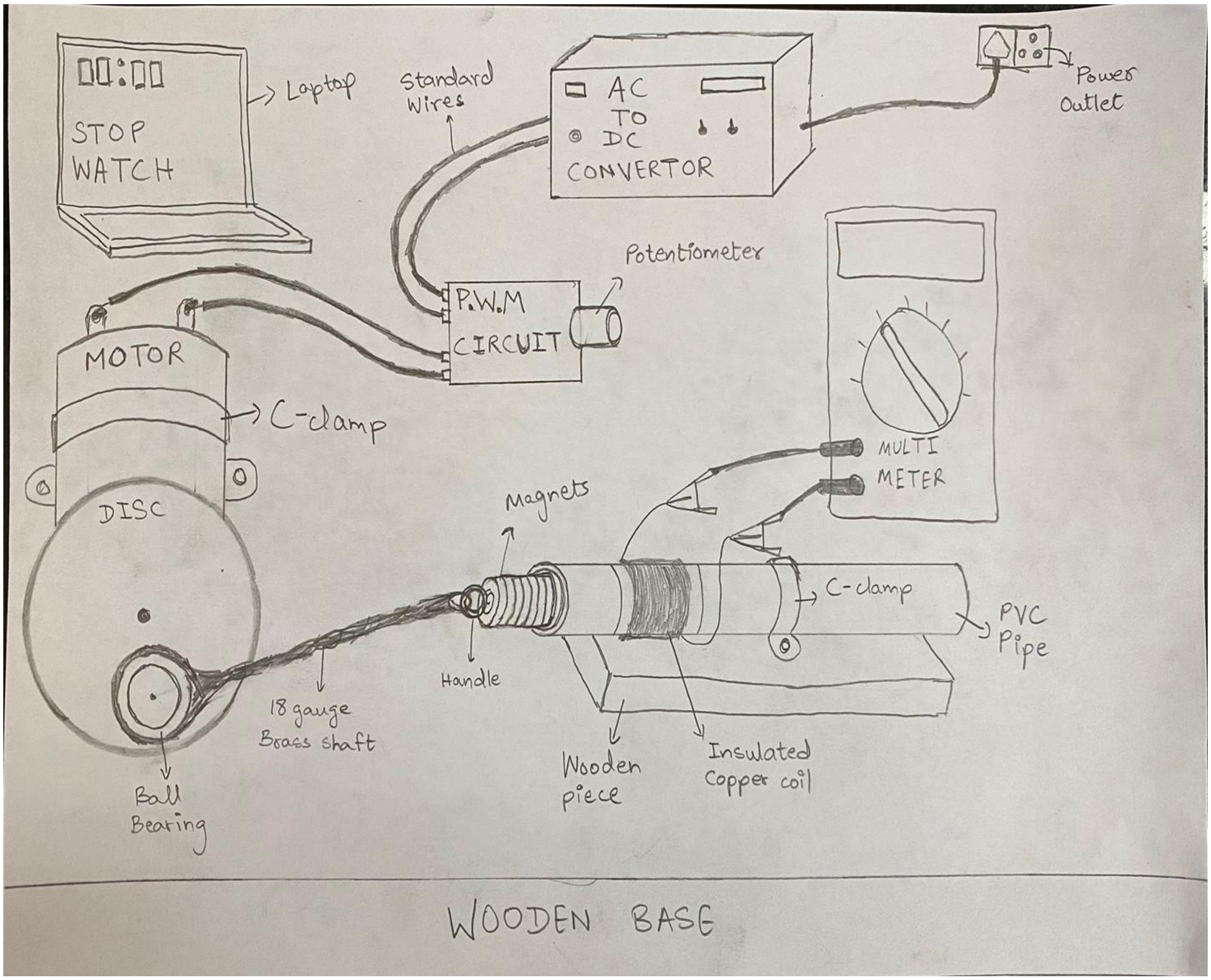

Figure 3.4.1

3.5 Data collection procedure

1. Record the room temperature.
2. Turn the power on in the AC/DC convertor and the multimeter on AC mode.
3. Turn the potentiometer on the PWM circuit until the motor starts to move.
4. Vary the rotational speed by increasing the power supplied to the motor by turning the potentiometer in the PWM circuit in a clockwise direction until significant voltage is produced in the multimeter.
    i. Here, I considered any values greater than 0.200V to be significant.
5. Start the recording, stop it after 10s.
6. Repeat steps 5 and 6 until maximum speed of the motor is achieved.
7. Record the room temperature again.

4 Data presentation

4.1 Period, rate of change of magnetic flux and EMF

Time	room temperature - K
Before the experiment	293.65
After the experiment	293.68

Table 4.1.1

apparatus	dimensions (meters)	absolute uncertainty	percentage uncertainty
individual magnet's radius	0.0075	0.00001	0.133%
individual magnet's thickness	0.0030	0.00001	0.333%
copper coil radius	0.0115	0.00001	0.087%
copper coil length	0.0264	0.00001	0.038%

Table 4.1.2

All the data was recorded on a slow-motion camera. As oscillator creates an oscillating motion of the magnet, one whole oscillation of the rotating disc meant one whole oscillation of the magnet. Oscillations can be timed using the stopwatch in the video.

Calculating average period of the different rotational speeds of the oscillator:

sr.no	trial one (seconds)	trial two (seconds)	trial three (seconds)	trial four (seconds)	trial five (seconds)	trial six (seconds)	average (seconds) (3dp)
1	0.39	0.51	0.52	0.48	0.38	0.42	0.45
2	0.59	0.41	0.43	0.47	0.55	0.45	0.48
3	0.61	0.63	0.42	0.40	0.44	0.50	0.50
4	0.62	0.65	0.53	0.47	0.51	0.52	0.55
5	0.67	0.69	0.69	0.63	0.61	0.61	0.65
6	0.88	0.85	0.79	0.73	0.72	0.73	0.78
7	0.88	0.86	1.06	1.00	0.97	0.93	0.95
8	1.36	1.35	1.39	1.33	1.34	1.33	1.35
9	1.39	1.41	1.59	1.51	1.46	1.44	1.47

10	1.69	1.71	1.73	1.77	1.70	1.70	1.72

Table 4.1.3

Calculating average EMF induced in the coil for different periods of the oscillator:

sr.no	trial 1 (voltage)	trial 2 (voltage)	trial 3 (voltage)	trial 4 (voltage)	trial 5 (voltage)	trial 6 (volage)	average (voltage) (4dp)
1	0.2390	0.2250	0.2190	0.2530	0.2335	0.2525	≈ 0.2370
2	0.2445	0.2485	0.2870	0.2790	0.2780	0.2750	≈ 0.2687
3	0.2860	0.3090	0.2900	0.3050	0.3040	0.3070	≈ 0.3002
4	0.4050	0.4070	0.4050	0.4050	0.4070	0.4090	≈ 0.4063
5	0.5290	0.5410	0.5400	0.5430	0.5365	0.5380	≈ 0.5379
6	0.7210	0.7170	0.6960	0.6790	0.6605	0.6520	≈ 0.6876
7	0.8220	0.8240	0.8320	0.8380	0.8410	0.8340	≈ 0.8318
8	0.9550	0.9580	0.9620	0.9670	0.9700	0.9720	≈ 0.9640
9	0.9800	0.9780	0.9775	0.9790	0.9870	0.9880	≈ 0.9816
10	1.0060	1.0255	1.0280	1.0280	1.0310	1.0370	≈ 1.0259

Table 4.1.4

The average uncertainty is: (Maximum reading–minimum reading)/2

sr.no	period (seconds)	maximum reading (seconds)	minimum reading (seconds)	average uncertainty (max-min)/2 (2dp)	percentage uncertainty (2dp)
1	0.45	0.52	0.38	0.07	15.56
2	0.48	0.59	0.41	0.09	18.75
3	0.50	0.63	0.40	0.12	24.00
4	0.55	0.65	0.47	0.09	16.36
5	0.65	0.69	0.61	0.04	6.15
6	0.78	0.88	0.72	0.08	10.26
7	0.95	1.06	0.86	0.10	10.53
8	1.35	1.39	1.33	0.03	2.22
9	1.47	1.59	1.39	0.01	0.68
10	1.72	1.77	1.69	0.04	2.33

Table 4.1.5

sr.no	EMF induced (volts)	maximum reading (volts)	minimum reading (volts)	average uncertainty (max-min)/2	percentage uncertainty
1	≈0.2370	0.253	0.219	0.017	7.173
2	≈ 0.2687	0.287	0.246	0.021	7.815
3	≈ 0.3002	0.309	0.286	0.012	3.997
4	≈ 0.4063	0.409	0.405	0.002	0.492
5	≈ 0.5379	0.543	0.529	0.007	1.301
6	≈ 0.6876	0.721	0.652	0.035	5.09
7	≈ 0.8318	0.841	0.822	0.010	1.202
8	≈ 0.9640	0.972	0.955	0.009	0.934
9	≈ 0.9816	0.988	0.978	0.005	0.509
10	≈ 1.0259	1.037	1.006	0.016	1.56

Table 4.1.6

4.2 Theoretical calculations

EMF induced in the coil is AC which normally follows a sinusoidal or a co-sinusoidal curve. The multimeter cannot display all the values in that curve; therefore, an average is needed, but normal average wouldn't work because the wave produced from the EMF values is positive for half a cycle and negative for the other half, resulting in the average being 0. Therefore, the multimeter uses root mean square value of all the values in the curve. The data recorded is the r.m.s value and the only significant data that can be extracted from that value is the peak voltage induced.

Peak voltage=r.m.s value$\times\sqrt{2}$

The same peak voltage can be calculated theoretically too, only if the $\Delta B/\Delta t$ can be known. From faraday's formula the highest $\Delta B/\Delta t$ will induce the maximum amount of EMF

.

Assume that the disc moves on a 2D plane. The motion of the magnet is dependent on the x coordinate of the ball bearing on the disc, change in the x coordinate will make the magnet move, though it cannot be said that they move at the same rate since the shaft connected makes an angle with the horizontal. Therefore, the magnet is moving slower than the x coordinate of the ball bearing on the disc, but the difference is minute, and it is assumed that their rates are identical. One complete oscillation of the disc will also mean one whole oscillation of the magnet's motion which will help us calculate the velocity of the magnet's motion.

The range of motion of the magnet provided by the disc used is = 0.050±0.00001m. The coil is placed at the center of the range of motion of the magnet. Assume the coil to be extremely dense with 200 turns so that it become a single thin disc, making the calculations easier as now the whole coil is treated as a single point in the middle of the range of motion. Range of motion of the magnet:

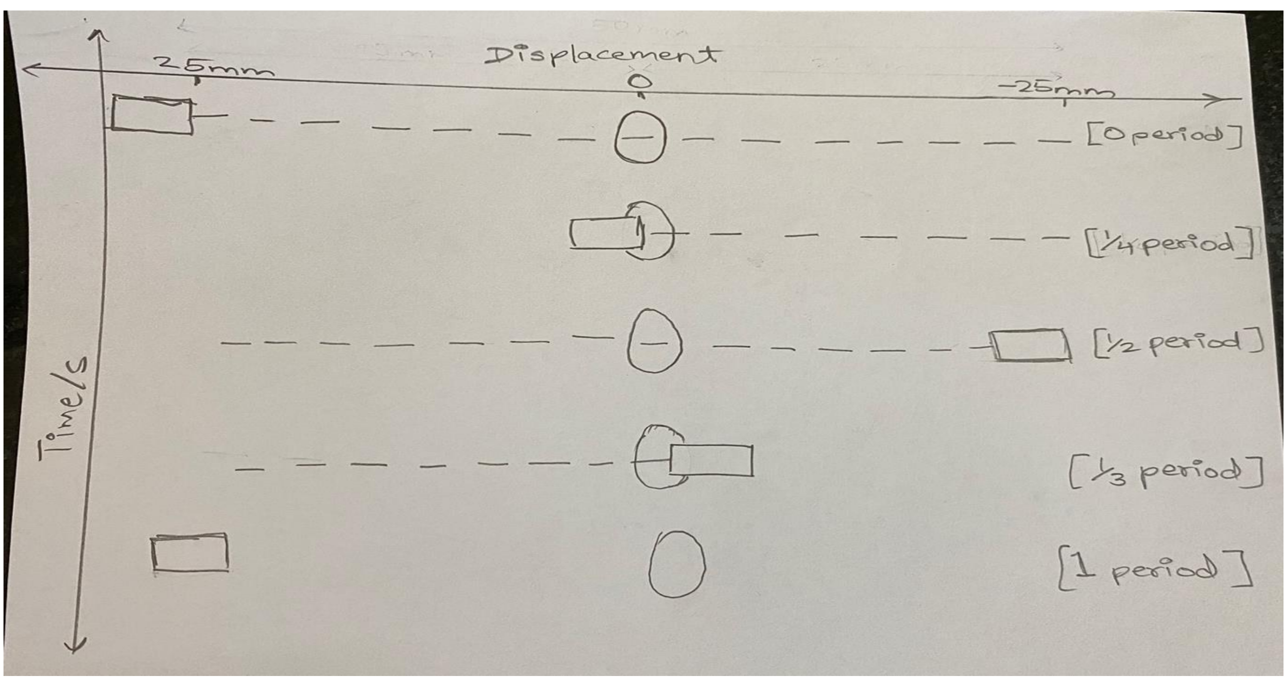

Figure 4.2.1

If the motion of the x coordinate of the bearing is observed and if the starting position is one that provides the magnet the furthest distance from the coil which is =0.025±0.00001 m, then it can be derived that the x coordinate of the bearing makes a co-sinusoidal function when graphed against time.

The graph produced will be different for all periods of the oscillator since frequency of a cosine function is dependent on the period of the wave. The relationship between period and frequency is Frequency=$\frac{1}{T}$, where T is the period. The amplitude of the function is not considered as only the motion provided by the oscillator is being analyzed. As a result, a general formula for x-coordinate (of the bearing) vs time is:

D(t)=cos (ft)

where f=frequency

t=time.

(Experimental periods of the oscillations are used for theoretical calculations)

x-coordinate vs time functions of respective periods:

period, T, seconds	frequency, f, Hz	function
0.45	2.22	cos(13.95t)
0.48	2.08	cos(13.07t)
0.50	2.00	cos(12.57t)
0.55	1.82	cos(11.44t)
0.65	1.54	cos(9.68t)
0.78	1.28	cos(8.04t)
0.95	1.05	cos(6.60t)
1.35	0.74	cos(4.65t)
1.47	0.68	cos(4.27t)
1.72	0.58	cos(3.64t)

Table 4.2.1

For example, period=0.45s.

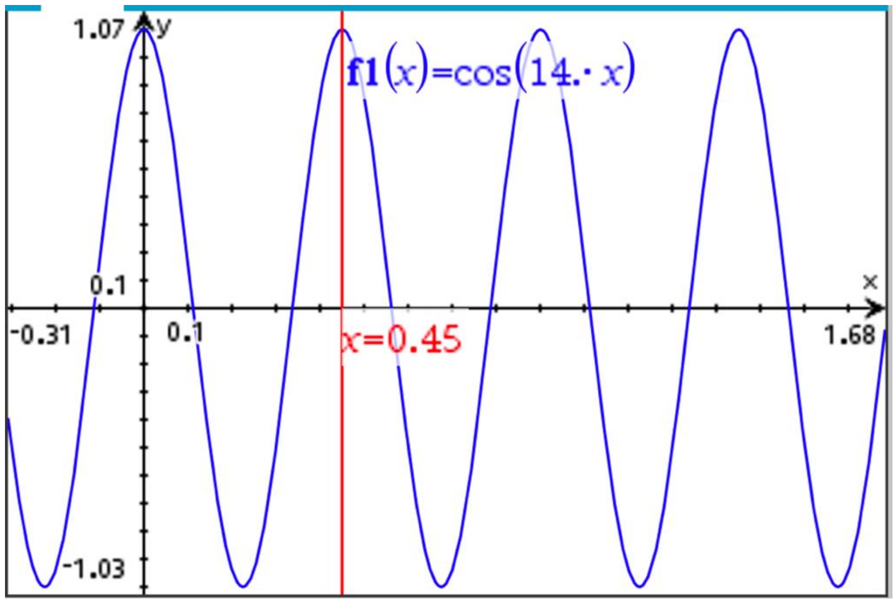

Figure 4.2.2

∆x/∆t is the differentiation of the above graph=to the velocity of magnet:

D′(t)=-13.95×sin (13.95t)

Therefore,

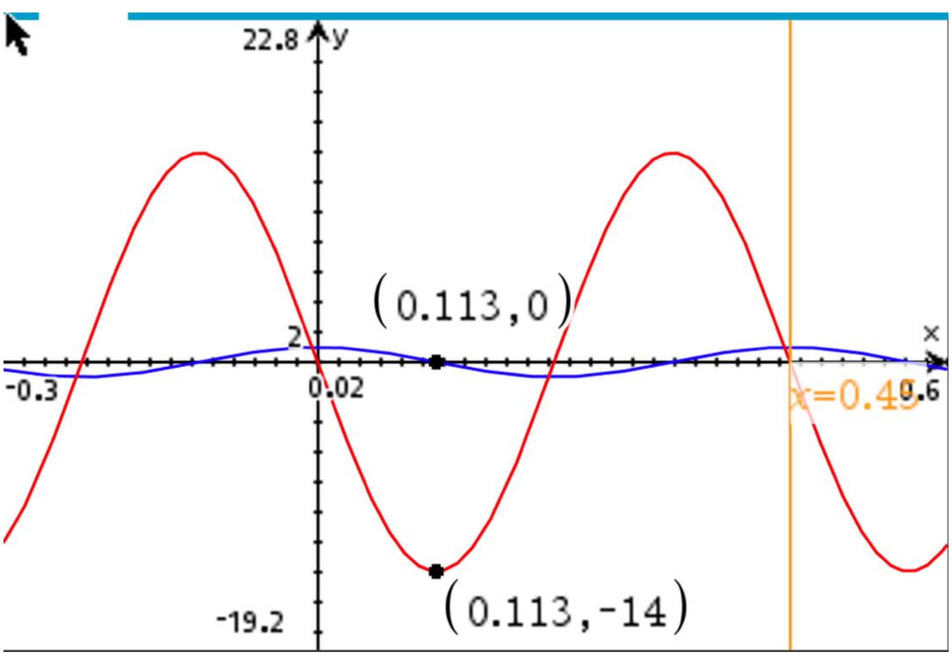

Figure 4.2.3

The maximum $\Delta x/\Delta t$ is at the point (.113, -14) here the time is exactly ¼ of the period (0.45s), meaning that the magnet has the highest velocity at t = ¼ period. ¼ of the period is when the magnet is directly under the coil. This happens twice at two different times, t=1/4 period and t=3/4 period. This means that the peak voltage is produced twice in one whole oscillation.

Back to faraday's law of induction:

EMF = $-N\times A\times\frac{\Delta B}{\Delta t}$

Using the definition of differentiation, $\frac{\Delta B}{\Delta t}$ is essentially the gradient of the function of magnetic field vs time. We can calculate $\frac{\Delta B}{\Delta t}$ by measuring the magnetic field at two distinct points from the coil and dividing the difference by the time taken to cover that distance. The velocity of the magnet is not constant, so it is very important to take the two points appropriately, the closer the points are, the more accurate the data.

For my investigation I divided half of the range of motion into 10 equal parts and try to find the change in magnetic field for two consecutive points near the coil. The formula for magnetic field is as following:

$$B(z)=0.6\times\left(\frac{0.021+z}{\sqrt{(5.625E-5)+(0.021+z)^2}}-\frac{z}{\sqrt{5.625E-5+(z)^2}}\right) \qquad (2)$$

Here, z is the distance between the pole face and the coil.

The range of motion of the coil for ¼ of the period is exactly 0.025±0.00001m therefore I selected the two points such that the distance between the magnet and the coil is minimized. The two points are z=0m and z=0.0025m from the coil. Time taken to travel 0.025m is ¼ of the period, therefore time taken to travel 0.0025m will be 1/40 period.

∆B for the two points=

B (0) $=0.6\times(\frac{0.021}{\sqrt{(5.625E-5)+(0.021)^2}})$

B (0) =0.565045T

And,

B (0.0025) $=0.6\times(\frac{0.021+0.0025}{\sqrt{(5.625\mathrm{E}-5)+(0.021+0.0025)^2}}-\frac{0.0025}{\sqrt{5.625\mathrm{E}-5+(0.0025)^2}})$

B (0.0025) =0.381859T

Therefore, ∆B is: 0.565045–0.381859=0.183186T

Using theoretical ∆B in faraday's law of induction, I create a function for induced EMF in terms of time taken for the magnet to travel 0.0025m, which is 1/40 of the period.

$EMF=-N\frac{\Delta\Phi}{\Delta t}$

$EMF=-N\times A\times\frac{\Delta B}{\Delta t}$

$EMF=-N\times A\times\frac{\pm 0.183186}{\Delta t}$

Since A and N are constants, the equation is:

$EMF=-200\times 0.000415\times\frac{\pm 0.183186}{\Delta t}$

$EMF=\frac{\pm 0.015204}{\Delta t}$ Δt =1/40×period of the oscillator.

Therefore,

$$\text{EMF}=\frac{\pm 0.015204}{\frac{1}{40}\times \mathrm{T}}$$

$$\therefore \text{EMF}=\frac{\pm 0.608178}{\mathrm{T}} \qquad (3)$$

Displacement of the magnet with respect to coil=positive when the magnet is on left side of the coil and produced EMF=negative. When magnet is on right, then the displacement=negative, and induced EMF=positive.

In equation (3) I am varying the IV by only varying the period T

Theoretical data table

Sr.no	Period of the oscillation	Δtime	Δ magnetic field	$\frac{\Delta\Phi}{\Delta t}$	Maximum EMF induced
1	0.45	0.01125	0.183186	0.006758	1.35151
2	0.48	0.01200	0.183186	0.006335	1.26704
3	0.50	0.01250	0.183186	0.006082	1.21636
4	0.55	0.01375	0.183186	0.005529	1.10578
5	0.65	0.01625	0.183186	0.004678	0.935659
6	0.78	0.01950	0.183186	0.003899	0.779716
7	0.95	0.02375	0.183186	0.003201	0.640188
8	1.35	0.03375	0.183186	0.002253	0.450503
9	1.47	0.03675	0.183186	0.002069	0.413727
10	1.72	0.04300	0.183186	0.001768	0.353592

Table 4.2.2

Theoretical EMF vs period:

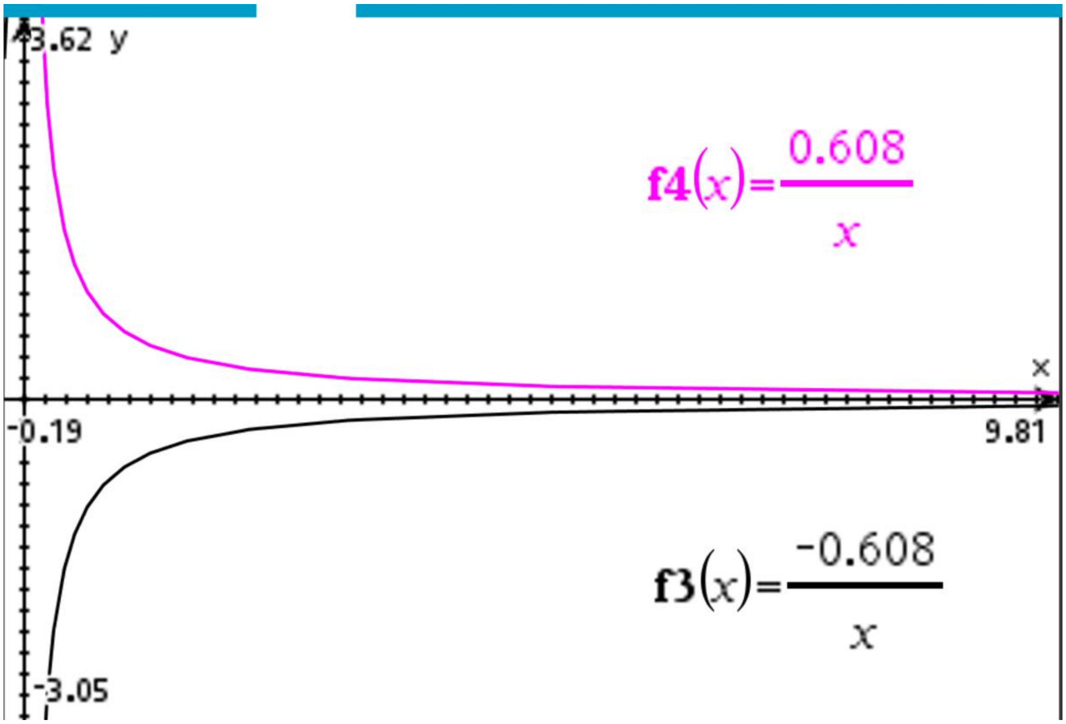

Figure 4.2.4

As evident in the graph the values follow an inverse relationship which is seen in the equation of the function. Therefore, EMF and period of the oscillator are inversely proportional to each other, a lower value will induce a larger EMF according to the above rational function.

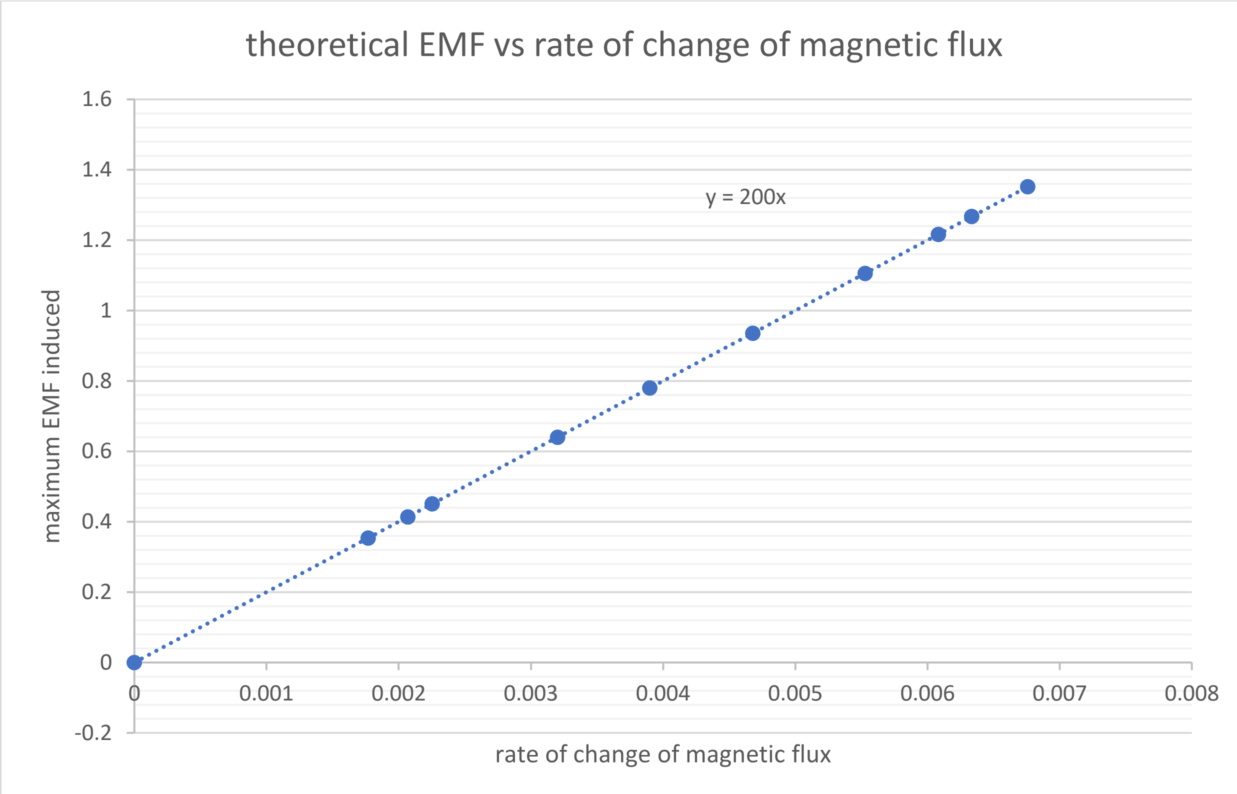

Figure 4.2.5

The graph above follows a perfect linear relationship producing a straight line with a gradient equal to 200. As Faraday's law predicts a faster rate of change of magnetic flux will induce more EMF. The gradient of the best fit line is the number of turns in the coil which for my investigation is 200.

4.3 Data analysis

Experimental values for period and change in magnetic field are chosen to calculate $\frac{\Delta\Phi}{\Delta t}$ and graph them:

sr. no	period/T	rate of change of magnetic flux	EMF induced (r.m.s value)	maximum EMF induced
1	0.045	0.006758	1.026	1.451
2	0.048	0.006335	0.982	1.389
3	0.050	0.006082	0.964	1.363
4	0.053	0.005529	0.832	1.177
6	0.065	0.004678	0.688	0.973
7	0.078	0.003899	0.538	0.761
8	0.095	0.003201	0.406	0.574
9	0.135	0.002253	0.300	0.424
10	0.147	0.002069	0.268	0.379
11	0.172	0.001768	0.237	0.335

Table 4.3.1

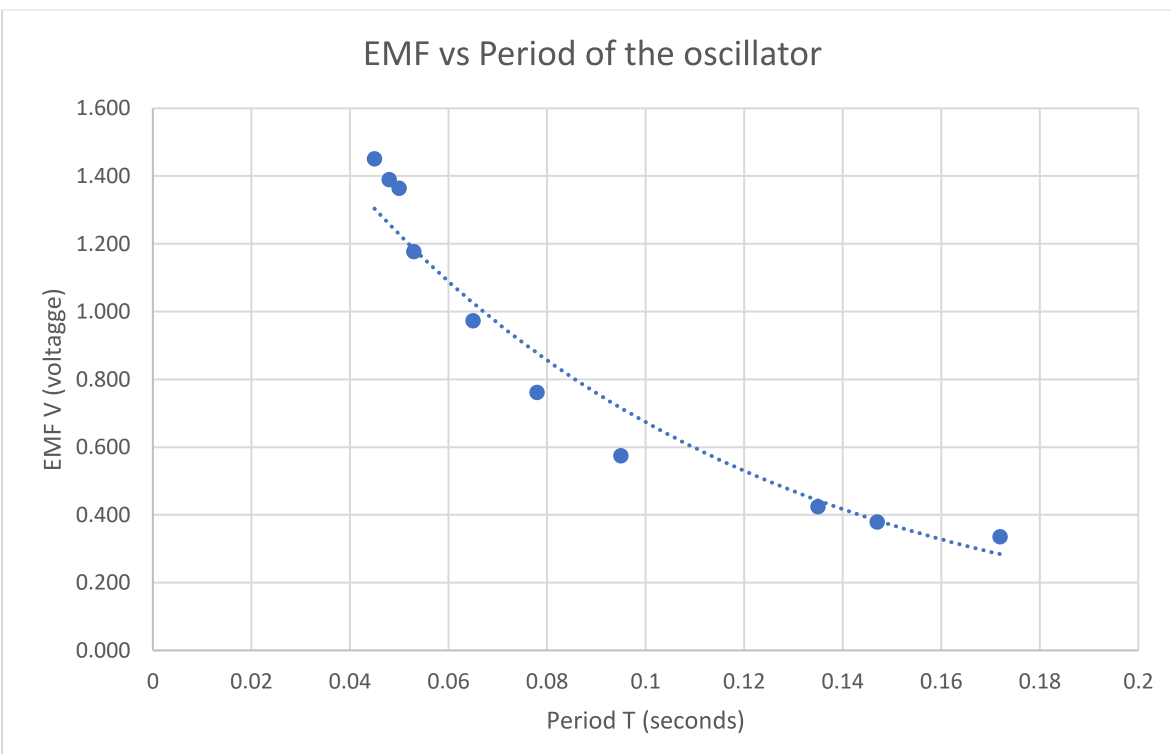

figure 4.3.1

As expected, period of the oscillator will follow an inversely proportional relationship to the EMF induced. On decreasing the period of the oscillator, the motion of the magnet increased resulting in larger $\Delta\phi/\Delta t$. Therefore, increased induction of EMF. The trend line observed seems exponential and the shape of the best fit line closely resembles the function y = 1/x. When compared to figure 4.2.4, both the functions portray similar characteristics, like the inverse correlation that the variables obey.

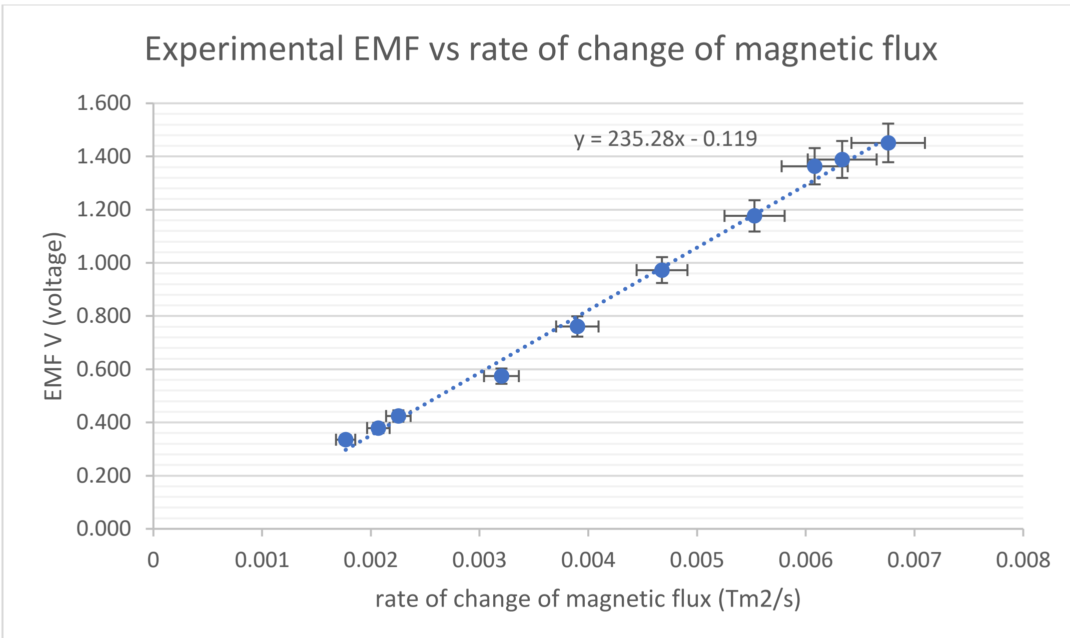

Figure 4.3.2

The second graph of EMF vs $\frac{\Delta\Phi}{\Delta t}$ closely follows a linear relationship. The best fit line, if extrapolated will not start from the origin because of the assumptions made, and the inaccuracy of the instruments used which increased random error in the data.

With this data, a graph of peak theoretical EMF and experimental EMF can be produced against $\frac{\Delta\Phi}{\Delta t}$.

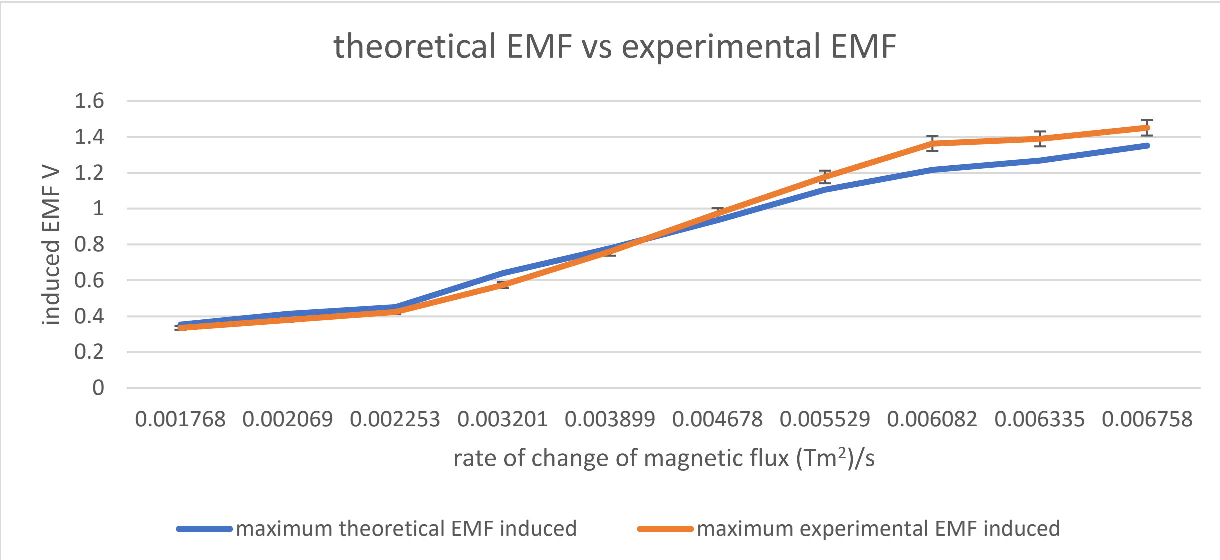

Figure 4.3.3

When the theoretical and the experimental maximum induced EMF are plotted against each other for the respective $\frac{\Delta\Phi}{\Delta t}$, a strong positive correlation is observed as predicted by Faraday's law. The trends of both the lines are identical with some variance. The experimental values conform well with the theoretical values which increases credibility.

5 Evaluation

5.1 Conclusion

Through this investigation, a direct relationship between the IV and DV is established. Aim of the investigation was to understand faraday’s law of induction, which was successfully confirmed and a numerical relationship between them was also verified.

$$\text{EMF}=-N\frac{\Delta\Phi}{\Delta t}$$

5.2 Evaluation

Experimental data was my investigation’s strength, backed by the theoretical calculations. Implying that, the experiment had less systematic errors. One of the reasons for such high accuracy like the use of an oscillator. If by any chance the frequency of the oscillation was to change in the middle of the data collection even by a small magnitude, the voltage induced would change drastically, increasing the systematic error.

On the other hand, the use of sensitive multimeters for such small values resulted in increased random error. Random error was reduced by taking six trials for each increment in the $\frac{\Delta\Phi}{\Delta t}$. Also, probes were insulated using tape where the coil was connected, protecting the connection from unwanted stimuli.

Moreover, the inaccuracy of the stopwatch used could also be a possible source of random error. Refresh rate of a screen is how fast a screen refreshes which dictates how many milliseconds it displays. Even with 120 Hz as the setting for my refresh rate on my laptop, it still skipped on an average 0.03s. This increased the uncertainty of the data. Solution to this problem was to take multiple trials for measuring the period of the oscillator.

Also, the slow-motion camera used had a moderate number of frames per second capture. When recording the higher frequencies of the oscillator, I observed that the speed of the bearing was so high that it was hard for camera to capture it properly.

The difference in the theoretical and experimental yields is due to the assumptions made. One such assumption was how I considered the whole coil to be a single loop. Therefore, all the calculations were made using this assumption, which is not true because the coil has length and there are some loops that are closer to the magnet at a certain point in time than other loops, which increases the amount of EMF induced. For small values of $\frac{\Delta\Phi}{\Delta t}$, the theoretical yield is larger than the experimental yield which is again caused because of the assumption that the system is frictionless which was not the case.

Almost all my data points fell within the error bars except some. This could be due to a systematic error while analyzing the data or due to the propagation of large uncertainties resulting in significant inaccuracy. Even with those values, the data recorded was accurate and precise.

5.3 Limitations

- Friction between the magnet and the coil–systematic error as the motion of the magnet is slowed.
- Lower refresh rates of the stopwatch.
- Unequal increments of the IV–systematic error.
- Limited frames per second of the slow-motion camera.

5.4 Modifications

- A PWM circuit with more control over the speed of the motor preferred so more data can be collected so that more variations in speed are obtained.
- A PWM circuit with a scaled potentiometer.
- A slow-motion camera with more frames per second could produce more accurate data.
- A stopwatch display with a larger refresh rate.
- A coil which is as compact as possible with the least amount of length.
- The use of more magnets would produce larger EMF with more significant digits.

Majority of the energy production of the world uses electromagnetic induction which is fascinating. The applications of this investigation are endless. This technology is used in windmills, generators, fossil fuel power plants and even in electric cars.

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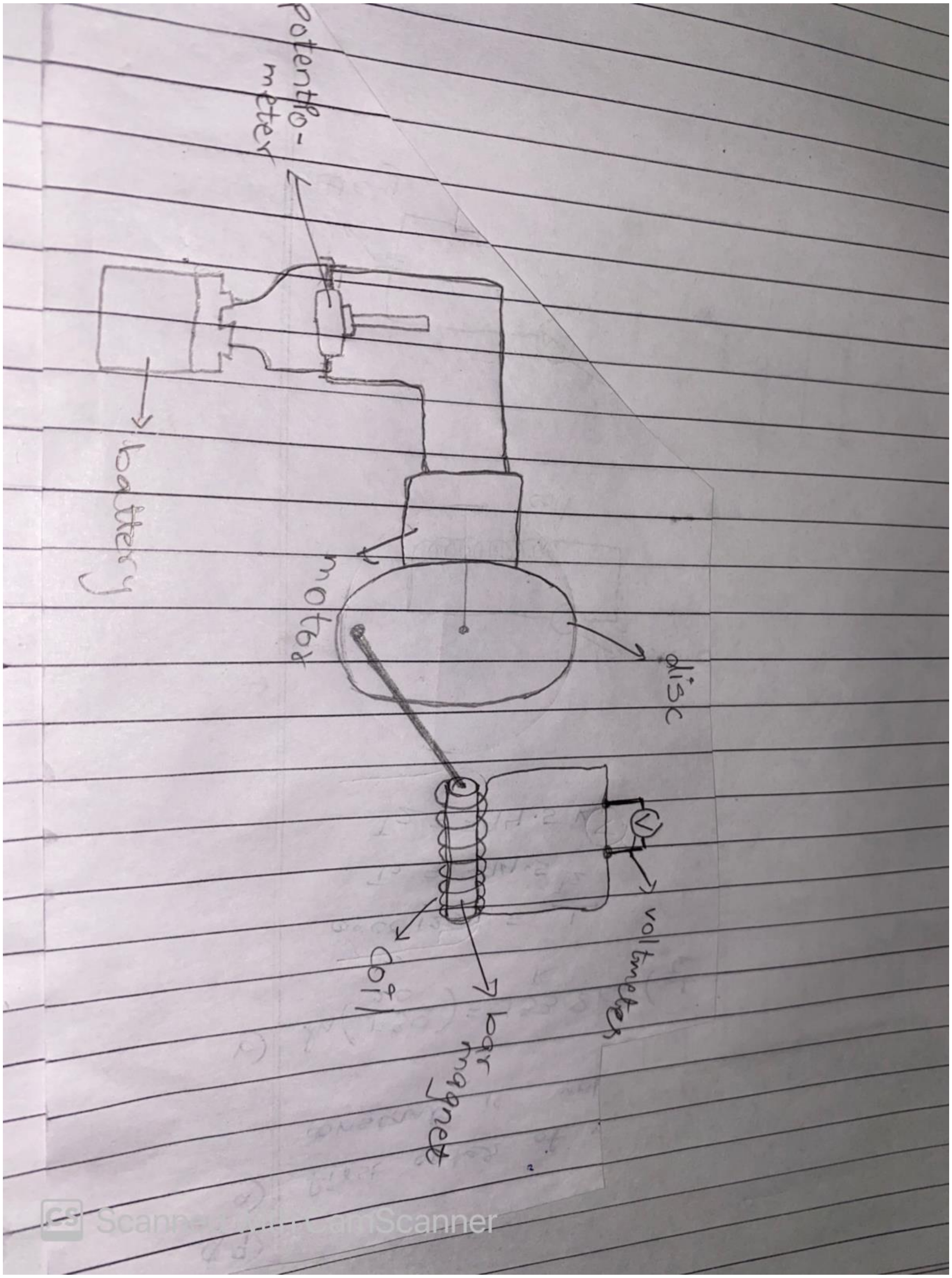
7 Resources used

- TI nspire cx II student software
- Digital stopwatch- https://stopwatch.online-timers.com/online-stopwatch
- Sketchbook

Appendix A

Early experimental setup



Appendix B

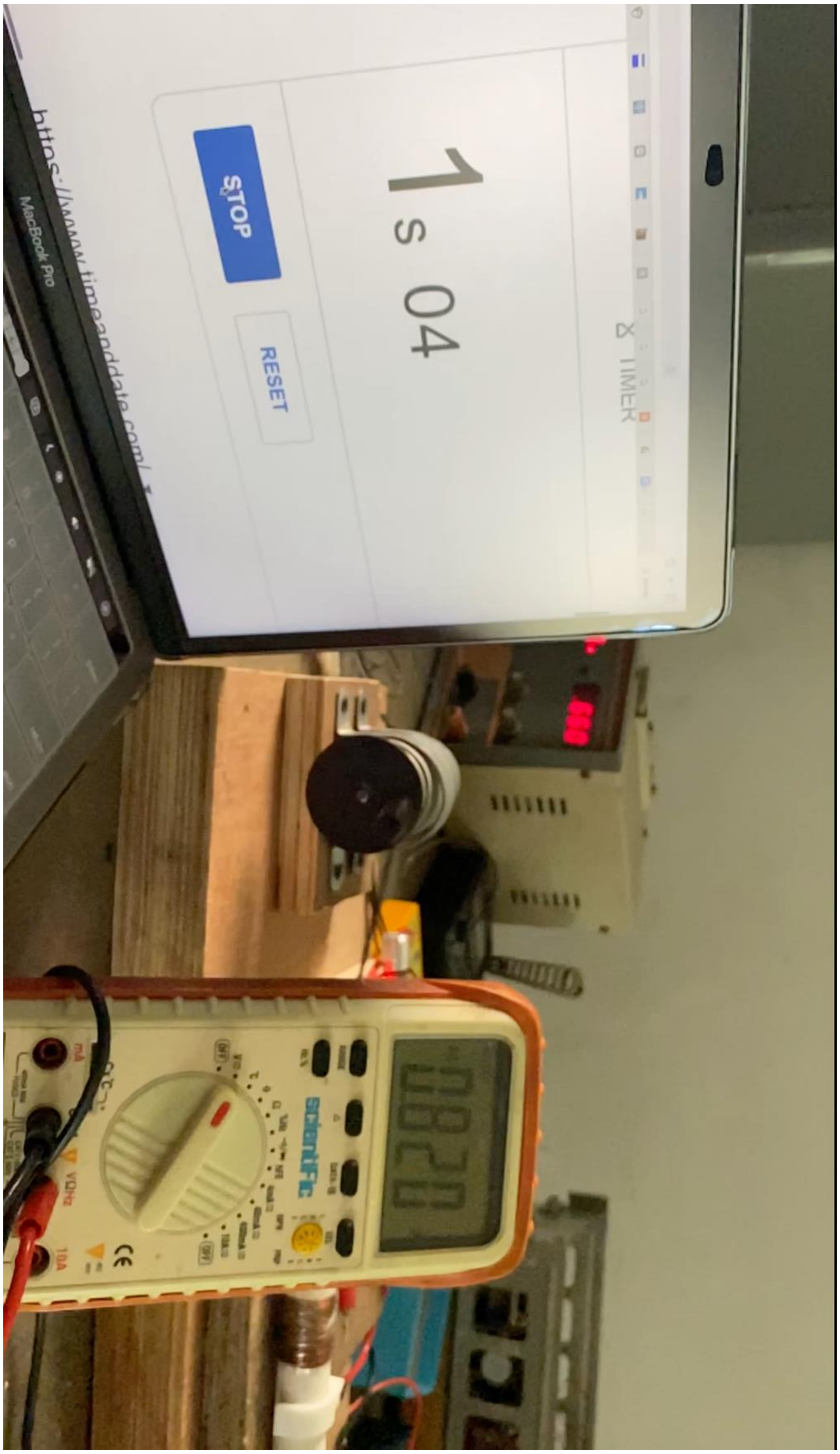
Picture of the coil

Appendix C

Picture of the magnets used

Appendix D

Original experimental setup



Appendix E

All the planning and calculations done for the investigation