Investigating the Relationship between RPM and Voltage Produced by a Generator

Introduction:

My grandfather and father have really inspired me to develop a passion for electricity. My grandfather worked at one of the largest power plants in Romania, he has helped me appreciate the importance of electricity in society and how reliant people are towards this technology. My father works as a contract manufacturer in the electronics field, and because of this he has always brought home tools and electronics that were no longer used, so that I could tinker with them. Because of this, my house is always full with circuit boards, motors, sensors, and a variety of electrical equipment that fascinated me at a young age. Soon enough I wanted to understand how they worked, so I decided to buy a couple of electronics kits. After a couple of years I developed a passion for building circuits and when we started learning topic 11 in physics class, I realized it was my favorite topic to study. After this realization, choosing a research topic became straightforward. I wanted to further examine the production of voltage using generators because I wanted to dive deeper in the field that my grandfather pursued. Doing this project would allow me to expand my knowledge on the study of electricity and magnetism while also learning more about my grandfather's career.

Background:

A few key concepts that are needed to understand how generators produce voltage are: magnetic flux and Faraday's law of induction. The magnetic flux formula provides the value of the magnetic field which passes through a given area. When a generator spins, there is a change in the angle, causing the magnetic flux to change.

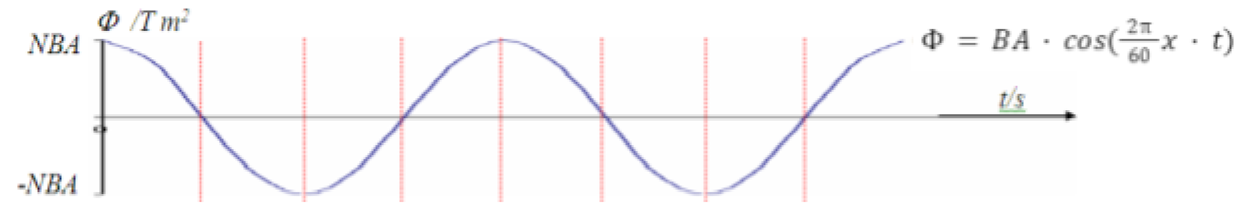
$$\Phi = BA \cdot cos(\theta)$$

$$\Phi = BA \cdot cos(wt)$$

$$\Phi = BA \cdot cos(\frac{2\pi}{60} \cdot x_{rpm} \cdot t)$$

Units:	Φ: magnetic flux (Wb)
B: magnetic field strength (Wb/m^2)	θ: angle between B and the normal to the area (rad)
w: angular speed (rad/s)	t: time (s)
x_{rpm}: Revolutions per minute (r/min)	A: area of coil (m^2)

θ is replaced with angular speed multiplied by time (wt) which is then converted to RPM multiplied by time ($\frac{2\pi}{60} \cdot x_{rpm} \cdot t$). From this formula it is observed that variation in the RPM will cause changes in the period, but will not impact the amplitude of magnetic flux. In my experimental setup the coil used is stationary while the magnet is spinning, therefore as time is changing the magnetic flux also changes over time. The magnetic flux over time graph should look like this:



Graph 1: Demonstration of change of magnetic flux over time while the generator is spinning.

As seen from the graph above, the fluctuations of the magnetic flux is dependent on the change in time. Faraday's law is used to relate the change in magnetic flux with the voltage induced in the coil.

$$\mathcal{E} = \; - N * \frac{\Delta\Phi}{\Delta t}$$

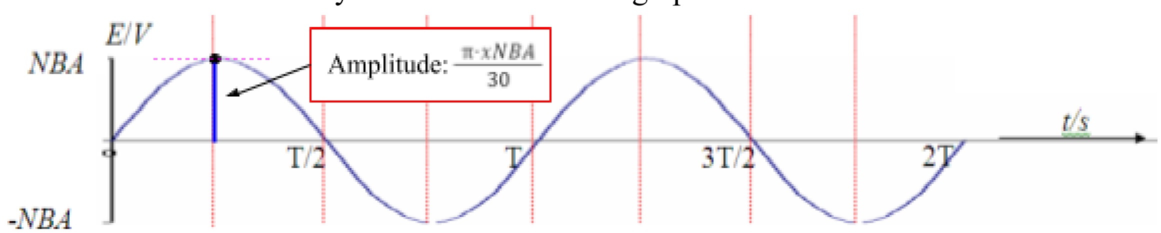
Change in magnetic flux over time is substituted from the formula derived on the previous page.

$$\mathcal{E} = \; - N \cdot BA \cdot \frac{cos(\frac{2\pi}{60} \cdot x_{rpm} \cdot t)}{\Delta t}$$

$$\mathcal{E} = \frac{\pi \cdot x_{rpm} \cdot NBA}{30} \cdot sin(\frac{\pi \cdot x_{rpm} \cdot t}{30})$$

Units:	$\mathcal{E}$: electromotive force (V) (Note that emf has the same meaning as voltage.)
$\frac{\Delta\Phi}{\Delta t}$: change in flux over change in time (Wb/s)	N: Number of coil turns (No unit)

The formula above would yield an emf over time graph that should look like this:



Graph 2: Voltage over time graph of a generator.

Because Faraday's law is the derivative of the magnetic flux multiplied by N, the phase difference between magnetic flux and induced emf will become $\frac{\pi}{2}$. The peak emf will be produced when magnetic flux is equal to 0, and no emf will be induced when magnetic flux is at its maximum and minimum values. This information can be applied to my IA, because increasing the RPM of the magnets will result in an increase in the amplitude of the function seen in graph 2, which will increase the peak voltages. Magnets rotating at a slower speed will result in smaller amplitudes which will lower peak voltages. From the equation $\mathcal{E} = \frac{\pi \cdot x_{rpm} NBA}{30} \cdot sin(\frac{\pi \cdot x_{rpm} \cdot t}{30})$, it is determined that the only ways to increase the peak voltages in a generator is by either increasing the RPM, the number of coil turns, the area of the coil or to use a stronger magnet (which increases B, the magnetic field strength).

To find the average measurements of the voltage, the root mean squared of the voltage must be found. This is done by taking the peak voltages and dividing it by root two. When dealing with AC voltage, root mean squared is more often used than peak voltages because it is more easily comparable to DC voltage. The formula to find the root mean squared of the voltage is $V_{rms} = \frac{V_o}{\sqrt{2}}$.

Design:

I. Research Question

What is the relationship between the RPM of a rotating generator and the induced electromotive force that is created by the generator?

II. Variables

Independent Variable:	-Revolutions per minute (RPM) of the rotating magnets There is a direct relationship between angular speed and voltage output of a generator. The rotating magnets' RPM will be varied at five different levels. The magnets will rotate at 5 different revolutions per minute: 100 rpm, 200 rpm, 300 rpm, 400 rpm, 500 rpm. This will be done through coding the Arduino, and a tachometer with uncertainty of ±0.1 RPM will be used to verify the correct RPM.
Dependent Variable:	-Induced peak voltages produced by the coil I will measure 15 peak voltages that occur in the coil using a voltmeter with an uncertainty of ±0.01 V.
Control Variables:	● Stepper motor **Reason:** No motor spins at the exact same RPM even when running the same code. **Method:** For maximum precision of RPM, the same stepper motor will be used throughout the experiment, and a small heatsink will be placed on the A4988 motor controller board to avoid overheating which may cause changes in RPM. ● Magnets **Reason:** Changing the magnets will change the magnitude of the magnetic field. **Method:** The same magnets were used, and a 3D printed part was created to ensure the orientation of the magnets would remain the same through the experiment.

	• Coil **Reason:** The area of the coil impacts the magnet flux (we can see this from the formula: $\Phi = BA \cdot cos(\theta)$), and the number of coil turns impacts the electromotive force (we know this from the formula $\mathcal{E} = -N \cdot \frac{\Delta\Phi}{\Delta t}$). **Method:** The same coil was used, the coil was also secured to a cylinder using sewing threads and tape to ensure the area of the coil does not change throughout the experiment. Coil dimensions: 500 turns, r ≈ 2.5 cm ± 0.05 cm, Area ≈ 19.6 cm^2 ± 0.78 cm^2 • Distance between coil and axis of rotating magnets **Reason:** Different distances between the coil and magnet change the voltage output, and magnetic flux within the coil. **Method:** The height of the coil was secured to a cylinder using sewing thread, and the motor was secured to a platform using a 3D printed part to ensure the distance between the axis of rotating magnets and the coil remain constant throughout the experiment.

III. Apparatus

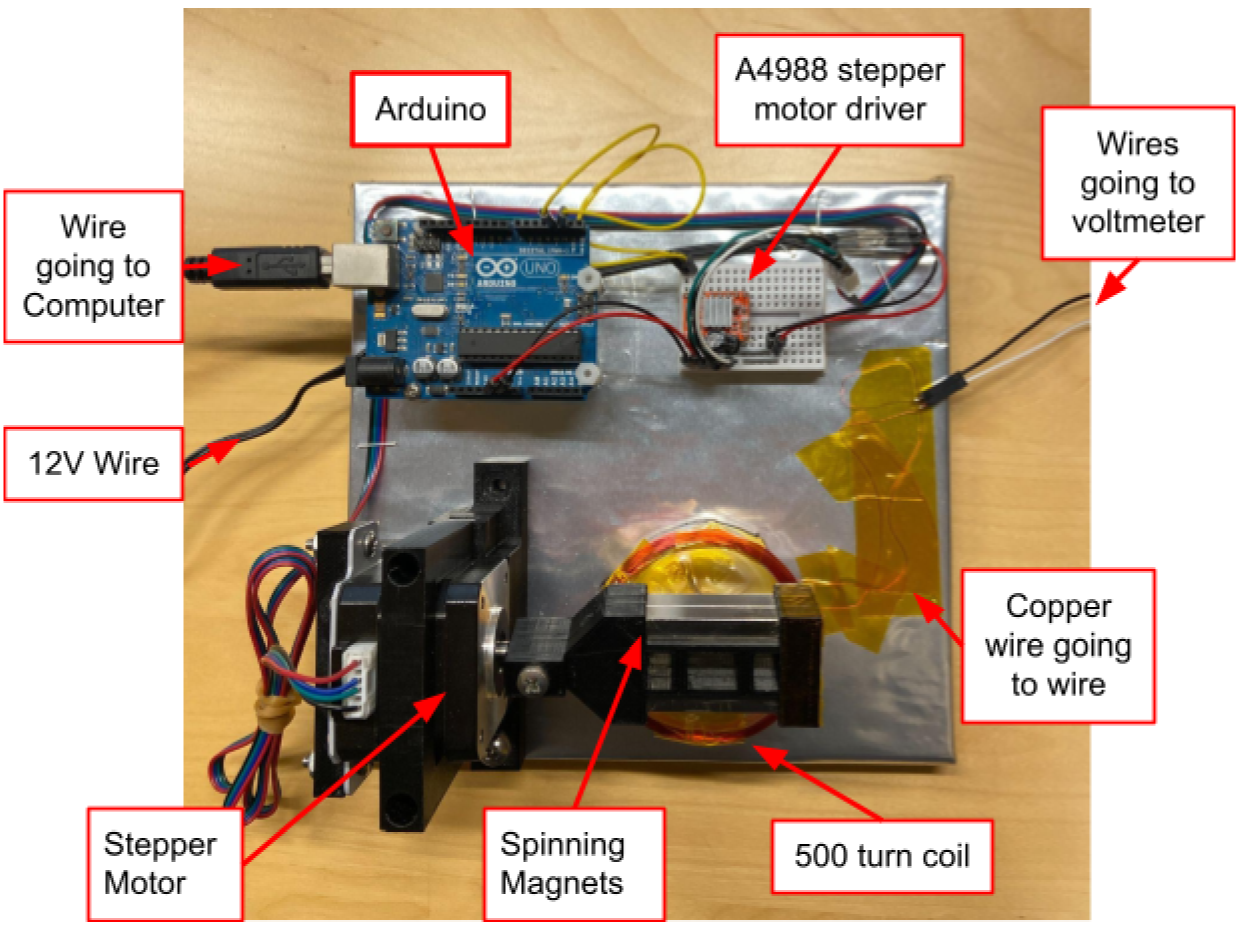


Figure 1: Picture of testing apparatus.

IV. Method

Range for the Independent Variable

The RPM was varied in intervals of 100 RPM because it allows the voltage to have a significantly larger difference between each measurement. A difference of 1 RPM between each experiment would cause a negligible difference in the voltage, so a difference of 100 RPM between each experiment was used in order to more accurately detect a trend in the voltage. Additionally, the range of 100 to 500 was chosen because the stepper motor's maximum RPM is around 550 RPM due to the voltage supply only being 12 V and due to the limitations of the A4988 chip. The decision to not use 550 RPM was to avoid overheating the A4988 chip.

Range for the Dependent Variable

In each trial, 15 voltage peaks were collected. 15 data points were collected because there were some large variations in the data collected for certain RPM's. At 100 RPM, the voltage measurements varied between 0.30 V and 0.46 V, in order to find a more precise average I opted to collect more data.

Materials for Apparatus

- NEMA-17 stepper motor
- 3D printed stepper motor mount
- Arduino UNO board
- A4988 stepper motor driver
- Voltmeter (±0.01 V)
- Laser tachometer (±0.1 RPM)
- Reflective tape (for tachometer)
- Copper coil (500 turns, radius ≈ 2.5 cm ± 0.05 cm, Area $\approx 19.6\ cm^2 \pm 0.78\ cm^2$)
- 4 rectangular neodymium magnets
- 3D printed rotor
- Breadboard
- 17.0 cm by 19.0 cm by 1.5 cm wooden platform (±0.05 cm)
- AC-to-DC adapter
- ESD shielding foil
- Laptop with Microsoft Excel and Vernier Graphical Analysis Software

Trial Run

A trial run was required in order to ensure that the RPM of the motor matched the desired RPM (this was done using a tachometer). If they did not match, the RPM was tweaked by using the Arduino board until the desired RPM was achieved.

V. Procedure

1. Program the Arduino board to rotate the stepper motor at 100 RPM.
2. Plug in the Arduino board and wait until the program starts running and the motor starts spinning.
3. Conduct a trial run using a tachometer to verify that the desired RPM of the motor matches the actual RPM. If the tachometer reading does not match the desired RPM, the code must be fine-tuned to ensure an accurate RPM. Ensure the reading of the tachometer is within a range of ± 0.1 RPM of the desired RPM.
4. Connect the coil to the voltmeter using 2 wires.
5. Let the motor spin until 15 peaks have been collected on the Vernier Graphical Analysis Software and then click the button that stops collecting data.
6. Unplug the Arduino board.
7. Record the 15 peaks in Excel and find the root mean squared of the voltage (using the formula $V_{rms} = \frac{V_O}{\sqrt{2}}$). The average of the 15 peaks will be substituted into V_O.
8. Repeat steps 1-7 at 100 RPM for another two times, to ensure that 3 trials have been conducted in total.
9. Repeat steps 1 through 8 at 200 RPM.
10. Repeat steps 1 through 8 at 300 RPM.
11. Repeat steps 1 through 8 at 400 RPM.
12. Repeat steps 1 through 8 at 500 RPM.

VI. Risk assessment

Use of 3D printing: 3D printers work by melting plastic which creates toxic fumes. In the long run it can become dangerous to 3D print in a closed environment, however to combat this issue an exhaust system was installed to redirect the fumes to an open window. Another safety precaution that I took was to use PLA material to 3D print my parts because it is biodegradable and produces less toxic fumes compared to other types of plastics when melted.

Use of strong magnets: The magnets used in this experiment were strong, in order to avoid injuries such as pinching I used gloves. Goggles were used when dealing with the magnets to avoid shards of magnet hitting the eye in the case of the magnets colliding and fragmenting. Proper magnet handling techniques were used, such as using a wedge when separating the magnets. To secure the magnets in place, I 3D printed a rotor to keep the magnets in a fixed position. I made sure to keep metal objects away from the magnet at a distance of around 15 cm to avoid damaging any equipment. I secured the Arduino board and the A4988 board to a piece of wood to avoid attraction to the magnet. An issue I ran into was that the wires going to the voltmeter would stick to the magnet while it was spinning, causing the wires to get tangled. In the future this could be fixed by designing a PCB board to eliminate the use of wires in the experiment.

Use of high voltage: In order to power the stepper motor, an AC adapter was used to convert the wall socket 120V AC input to 12V DC output. When dealing with live wires with high voltage, I made sure to keep the two terminals from touching each other by keeping them apart. I also connected the wires to a breadboard to avoid exposed wire.

Use of a drill: A drill was used to attach all the components of this experiment to a wooden board. To prevent injury or damage to the drill, I made sure to drill "pilot holes" first before drilling larger holes. I also used a drill to create my coil, by transforming it into a coil winding machine. I ran the drill at a low speed to ensure that I did not damage my coil winding machine.

Data Collection and Processing:

I. Collected data

Peak number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Peak voltage for trial 1 (V)	0.42	0.39	0.39	0.36	0.33	0.32	0.33	0.36	0.38	0.41	0.41	0.43	0.44	0.45	0.46
Peak voltage for trial 2 (V)	0.45	0.43	0.43	0.40	0.39	0.37	0.35	0.33	0.32	0.35	0.36	0.40	0.40	0.42	0.44
Peak voltage for trial 3 (V)	0.46	0.45	0.46	0.46	0.44	0.46	0.43	0.43	0.41	0.38	0.37	0.34	0.33	0.30	0.35

Table 1: Measured peak voltages (V) for 100 RPM.

II. Data Processing

The average peak voltage is calculated by adding all the peak voltages of a trial, dividing this value by 15 and then averaging all 3 trials. Next, the root mean square of this average needs to be found. This is done by substituting the average peak voltage into the equation $V_{rms} = \frac{V_o}{\sqrt{2}}$. Uncertainty can be found by subtracting the minimum peak voltage from the maximum peak voltage and multiplying the value by 0.3536 $(\frac{1}{2\sqrt{2}})$. The following will demonstrate a sample calculation of how the average V_{rms} was found.

Calculations for table 1:

V_{rms} is calculated by:

$$V_{Trial\ 1} = \frac{\sum_{i=1}^{15} V_i}{15} = \frac{V_1+V_2+V_3+V_4+V_5+V_6+V_7+V_8+V_9+V_{10}+V_{11}+V_{12}+V_{13}+V_{14}+V_{15}}{15}$$

$$V_{Average\ Peak} = \frac{V_{Trial\ 1}+V_{Trial\ 2}+V_{Trial\ 3}}{3}$$

$$V_{rms} = \frac{V_{Average\ Peak}}{\sqrt{2}}$$

Uncertainty of V_{rms} is calculated by:

$$\Delta V_{rms} = \frac{V_{Max}-V_{Min}}{2} \cdot \frac{1}{\sqrt{2}}$$

Sample calculation for 100 RPM:

$$V_{Trial\ 1} = \frac{0.42+0.39+0.39+0.36+0.33+0.32+0.33+0.36+0.38+0.41+0.41+0.43+0.44+0.45+0.46}{15} = 0.39\ V$$

$$V_{Trial\ 2} = \frac{0.45+0.43+0.43+0.40+0.39+0.37+0.35+0.33+0.32+0.35+0.36+0.40+0.40+0.42+0.44}{15} = 0.39\ V$$

$$V_{Trial\ 2} = \frac{0.46+0.45+0.46+0.46+0.44+0.46+0.43+0.43+0.41+0.38+0.37+0.34+0.33+0.30+0.35}{15} = 0.40\ V$$

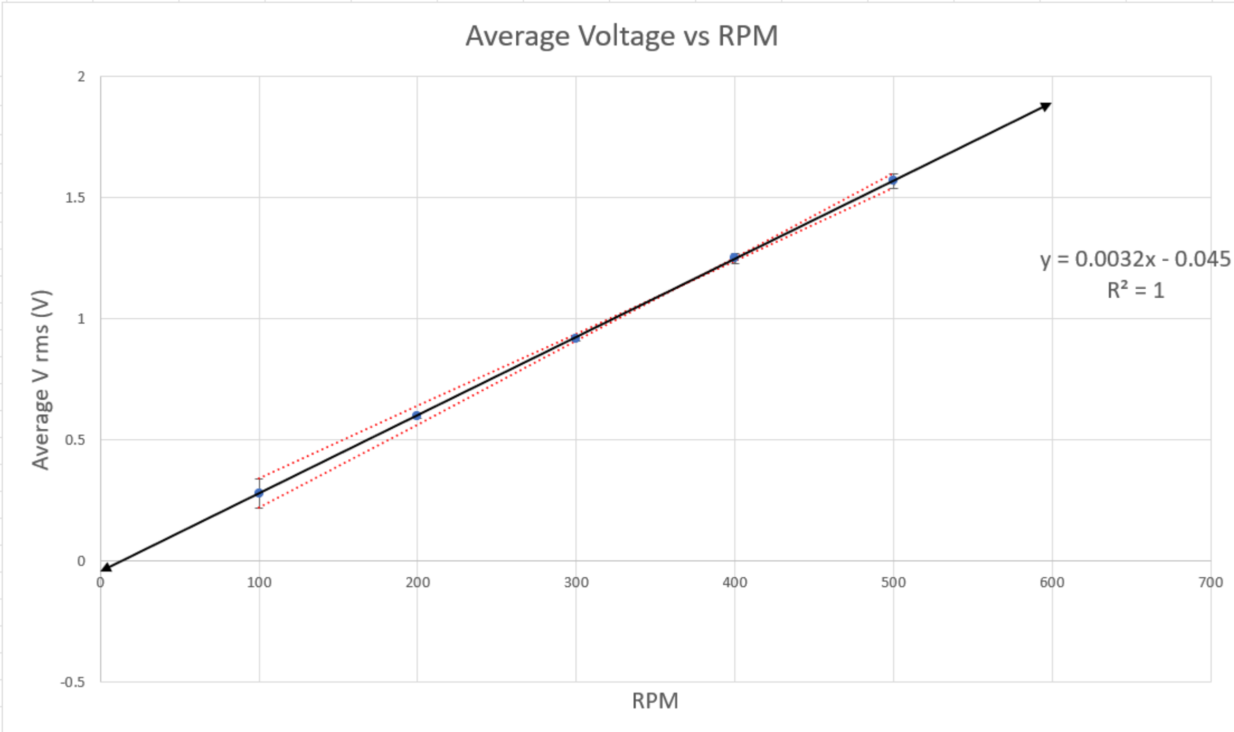
$$V_{Average\ Peak} = \frac{0.39 + 0.39 + 0.40}{3} = 0.40\ V$$

$$V_{rms} = \frac{0.40}{\sqrt{2}} = 0.28\ V$$

$$\Delta V_{rms} = \frac{0.46-0.30}{2} \cdot \frac{1}{\sqrt{2}} = 0.06\ V$$

RPM	Average V_{rms} (V)	Uncertainty ΔV_{rms} (V)
100	0.28	0.06
200	0.60	0.01
300	0.92	0.01
400	1.25	0.02
500	1.57	0.03

Table 2: The Average V_{rms} for each RPM with its uncertainty (ΔV_{rms})



Graph 3: Plotted data from table 2.

Conclusion:

After the data was processed, it can be observed from graph 3 that the voltage increases as the RPM of the generator increases. It is also visible that the average V_{rms} and the RPM of the generator are linearly proportional to each other. Another observation made is that the line of best fit does not have a y-intercept of 0. The line of best fit starts at (0, -0.045) instead of (0, 0) which demonstrates a downward shift in data, most likely due to low accuracy in the RPM measurements. Both theoretically and in practice it is impossible to generate a voltage at 0 RPM because there is no change in magnetic flux which means no voltage can be produced. It is also worth noting that the negative voltage present from around 0 to 14 RPM implies the generator is spinning in the opposite direction which contradicts the RPM value. This is a clear indication that there is systematic error present in this experiment and that the experiment poses some accuracy issues. This error could have originated from factors such as improperly calibrated measuring instruments, fluctuations in the RPM of the generator or a limited data range. These limitations will be further examined in the evaluation section.

This experiment observed high precision which can be seen by the extensive data collected in the tables in the appendix. Each RPM received three trials, with each trial containing 15 data points, for a total of over 45 values collected for each RPM. However some RPM's seemed to have more variation in the data collected than others, such as at 100 RPM where the uncertainty propagation was at its largest throughout this experiment. As RPM increases, uncertainty propagation decreases which may be as a result of the voltmeter being unable to collect data fast enough (it has a sample rate of 1000 samples/s). The error bars for RPM were not visible so they were excluded from the graph. The coefficient of determination which is present in graph 3 is equal to 1 which demonstrates high precision in the data collected. The line of best fit is within all 5 ranges of the error bars which further proves that the data is highly precise. An overview of the data plotted in graph 3 is that it has high precision but lacks accuracy due to a systematic error present in the experiment.

Evaluation:

Table 3: Possible weaknesses causing systematic error

Source of error and its effects	Significance and evidence	Improvements
Fluctuations in RPM: When running my experiment, I noticed that my A4988 stepper motor driver would often overheat while running for extended periods of time. Overheating this crucial component which controls the speed of the stepper motor may cause a reduction in the RPM.	This is highly significant because: -Any change in RPM will directly result in a change in voltage which is unaccounted for. -It was noticed that there were slight trends of the voltage decreasing in some trials as time went on which may be due to the A4988 chip overheating causing the RPM to decrease. Example: Table 1, trial 3.	A larger heat sink, as well as the application of thermal paste to the A4998 chip, would significantly reduce the undesirable overheating. This would allow the RPM to remain more consistent in value, improving the accuracy of the experiment and possibly bringing the y-intercept closer to (0,0).
Vibrations produced by the stepper motor: The stepper motor experienced vibrations while conducting the experiment. Here are some of the effects that it has on the performance of the motor: -The motor systematically overshoots or undershoots its position due to the inertia of the moving rotor. -The bearing inside was loose, which allowed the vibrations to move the shaft of the motor side to side -Vibrations from the stepper motor	This has low significance, because: -The motor overshooting or undershooting is very minimal and may only cause a small fluctuation in RPM. -The loose bearing inside would pose a problem only if the stepper motor was rotating at a higher RPM, however for the current application its effects were minimal. -The vibrations that the stepper motor produces between the distance of the magnets and the coil are not noticeable and are thus minimal.	Although the issue is not significant, a solution would be to: 1. Install a mechanical clean damper, which reduces the vibrations of the motor. 2. Either replace or use a higher quality bearing which allows for less movement in the shaft. 3. Use a gearbox which helps reduce the motor from under or overshooting. Overall, reducing the vibrations caused by the motor may minimally

would vibrate the wooden base, which vibrated the coil, which may cause small changes in the height between the coil and magnet. These effects could play a role in decreasing the RPM of the motor, hence shifting the y-intercept to a non-zero value.		reduce undesired RPM fluctuations which may slightly improve the accuracy of the experiment and bring the y-intercept closer to 0.
Imperfect calibration or use of tachometer: There may be systematic errors caused by the improper use of the laser tachometer. This could have resulted from external light interferences reflecting on the reflective tape which may cause some inaccuracies in the RPM readings. Since the intensity of the overhead classroom lighting remained constant, which may cause a minor shift in all RPM readings (systematic error).	This has low significance, because: -The tachometer is not required to be used in the dark, however reducing background light allows for better contrast between the dark spots and the reflective tape. The systematic error caused by this is minimal because my background lights were consistent in intensity. -The uncertainty of this device is also 0.1 RPM which means it has a relative uncertainty of around less than 1%, which demonstrates that the measuring instrument is precise.	Improvements could have been made such as measuring the RPM of the motor in a darker room by turning off the ceiling lights and closing my laptop screen. This would allow for more accurate RPM readings which in turn could bring the y-intercept closer to the origin. Another possible solution is to use a contact tachometer instead of a laser tachometer, which may be more accurate for this application.

Table 4: Possible weaknesses causing random error

Source of error and its effects	Significance and evidence	Improvements
Wire contact between alligator clips and coil wires: Poor contact between wires may result in inaccurate voltage readings.	This is highly significant because: -When setting up my experiment, I initially had difficulties receiving a voltage reading from my voltmeter, this was because I had contact issues between the alligator clips and the coil wire. -Some trials had to be repeated due to voltage reading issues caused by poor contact, and a lot of time was spent before finding the cause of	The improvement that I made was to solder the thin copper wires of the coil to larger wires which were then connected to the voltmeter. This increased the surface area of contact between the alligator clips of the voltmeter and the coil which led to more accurate readings.

	these sporadic voltage readings.	
Electrical field interference: Electrical field interferences from external sources could cause fluctuations in the voltage induced in the coil.	This is insignificant because: The electrical fields produced by the Arduino, the voltmeter and the laptop are negligible.	An improvement would be to increase the distance between the devices producing an electric field and the copper coil.
Magnetic field interference: The spinning magnets were very close to the stepper motor, which contains its own set of magnets. The close proximity of these two magnets could cause magnetic field interference which could lead to uneven and sporadic RPM changes.	This has low significance, because: -No significant changes in the RPM occurred while measuring the RPM of the shaft with the magnet attached. -There is a possibility that the magnets of the stepper motor may also be inducing their own voltage in the coil.	Possible improvements would be to increase the distance between the stepper motor and the magnets, which would decrease the overlap in their magnetic fields.

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Appendix

Table 5: Unprocessed data, measured peak voltages (V) for 200 RPM.

Peak number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Peak voltage for trial 1 (V)	0.84	0.84	0.85	0.85	0.85	0.85	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.87
Peak voltage for trial 2 (V)	0.84	0.84	0.84	0.84	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.86
Peak voltage for trial 3 (V)	0.87	0.87	0.87	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.85

Table 6: Unprocessed data, measured peak voltages (V) for 300 RPM.

Peak number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Peak voltage for trial 1 (V)	1.30	1.30	1.30	1.30	1.31	1.31	1.30	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.30
Peak voltage for trial 2 (V)	1.29	1.29	1.30	1.30	1.31	1.31	1.31	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.33
Peak voltage for trial 3 (V)	1.30	1.30	1.30	1.30	1.31	1.31	1.30	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.30

Table 7: Unprocessed data, measured peak voltages (V) for 400 RPM.

Peak number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Peak voltage for trial 1 (V)	1.74	1.74	1.74	1.74	1.74	1.74	1.74	1.74	1.74	1.74	1.74	1.74	1.74	1.74	1.74
Peak voltage for trial 2 (V)	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
Peak voltage for trial 3 (V)	1.76	1.77	1.77	1.76	1.77	1.77	1.76	1.77	1.77	1.76	1.77	1.77	1.76	1.77	1.77

Table 8: Unprocessed data, measured peak voltages (V) for 500 RPM.

Peak number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Peak voltage for trial 1 (V)	2.20	2.22	2.23	2.24	2.24	2.25	2.25	2.24	2.24	2.23	2.23	2.22	2.21	2.19	2.18
Peak voltage for trial 2 (V)	2.23	2.24	2.24	2.24	2.24	2.24	2.23	2.23	2.22	2.21	2.19	2.19	2.18	2.17	2.17
Peak voltage for trial 3 (V)	2.24	2.24	2.25	2.25	2.25	2.25	2.24	2.23	2.22	2.21	2.20	2.18	2.18	2.17	2.17