Introduction

When first considering a suitable topic for my physics IA, I was interested in investigating the relationships between energy production from turbines and variables that can increase efficiently. There are real world and local applications as my city is primarily powered by renewable hydro electricity. However, I quickly realise that this would not work as I could not manage to find a way to consistently turn a motor shaft at a high and stable speed. After this roadblock, I did a complete 180 and decided to do something regarding efficiency when using DC motor as I have always been fascinated in creating model vehicles and thus happened to have a few DC motors laying around my house. The topic of this IA will focus on such motors and their relationship with voltage and any real-world applications that can be considered.

Background

A DC motor are popular in the field of robotics due to their small size and high energy output (rice.edu). Because of this, they are optimal for powering wheels or other mechanical assemblies such as pullies. The 4 main attributes of a motor are speed, torque, power-in and power-out. Typical DC motors operate on 1.5 to 100 Volts (rice.edu). This experiment will use the volt range between 2 to 16 volts as 16 is the upper limit of the variable power supply I have access to. Voltage has always been one of the most primitive methods of controlling the speed of a DC motor.

Research Question

To what extent does the relationship between torque and voltage from a DC motor exist and how may it affect real world applications?

Hypothesis

I hypothesise that the relationship between voltage and rounds per minute to be linear as power is directly proportional to voltage in the equation $P = IV$. However, I would also assume that the peak torque for the motors used in this experiment align at 12 volts at that's what they are rated for. Real-world applications will be approached from the analyzed data.

Variables

Table 1: List of variables

Type	*Variable*	*Method and reason for control if needed*
Independent	Voltage	The 5 variations of this experiment would be the voltage: 16.0V, 12.0V, 8.0V, 4.0V, 2.0V.
Dependant	Angular speed of the motor shaft	The outcome of each trial will be the angular speed of the motor shaft that is recorded in rounds per minute (rpm)
	Current*	See asterisk.
Control	Temperature	All trials will be conducted at the same room temperature.
	Recording hardware	Audio will be recorded with the same microphone at the same distance from the motor shaft in each trial.
	Sound analysis software	Audio will be recorded and analyzed directly in Audacity software.
	Load on motor	Extra care was taken to place the lightest load on the motor in order to generate the buzz noise.

*The current was technically a controlled variable as it was not manually adjusted and was essentially uncapped for the motor. This allows voltage to be the only independent variable throughout the experiment with the small variations in current to simply be recorded as a secondary dependant variable. More on this in the procedure and evaluation.

Materials

Table 2: List of equipment

Name	*Usage*	*Quantity*
12V DC motor	Testing focus of the IA.	4
Variable power supply	Powers the motors and allows for the adjustments in voltage and current.	1
Roll of electrical tape	Create a tab on the smooth shaft of the motors in order to measure rounds per minute (rpm).	1
Multimeter	Though the variable power supply already has a built-in voltage and current reading, it is better to use a proper multimeter.	1
Connecting wire (with clamps)	Connects the motors to the variable power supply and makes sure that they do not come apart during each trial.	2
Microphone	Records the high frequency noise produced by the electrical tape tab and my finger.	1
Computer with Audacity installed	Analyzes the recorded buzz noise to determine how many rounds per minute the motor is spinning at.	1

Apparatus

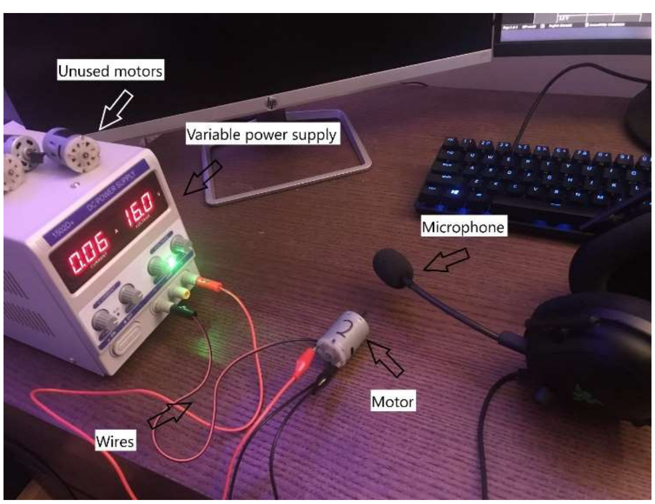

Figure 1: Apparatus

Procedure

1. Download and install *Audacity* on a computer with access to a microphone
2. Setup the variable power supply and wires near the computer
3. Prepare all the motors by adding a small tab of electrical tape to the end of each shaft
4. Label the motors from 1 to 4 with tape or a marker to prevent confusion when testing
5. Begin the data collection steps by connecting motor 1 to the power supply
    a. Make sure the current knob is set to max
6. Set the power supply to the desired voltage and the motor should begin running
    a. Record the current on the variable power supply
    b. Optionally, one could use a multimeter to check both the current and voltage readings as it provides more accurate readings
7. Start a recording on *Audacity*
8. Bring the shaft of the motor close to the microphone and brush a finger against the tab of electrical tape to create a buzzing noise
    a. It is important that minimal pressure is applied
9. Set down the motor and pause the audio recording after about 10 seconds
10. Magnify the audio recording and record the time interval between each buzz
    a. See figure 2
11. Record any other qualitative observations
12. Repeat steps 5 to 11 until all the motors and intervals of voltage have been recorded
13. Divide 60 by the period of time to get the RPM of the motor at the given voltage

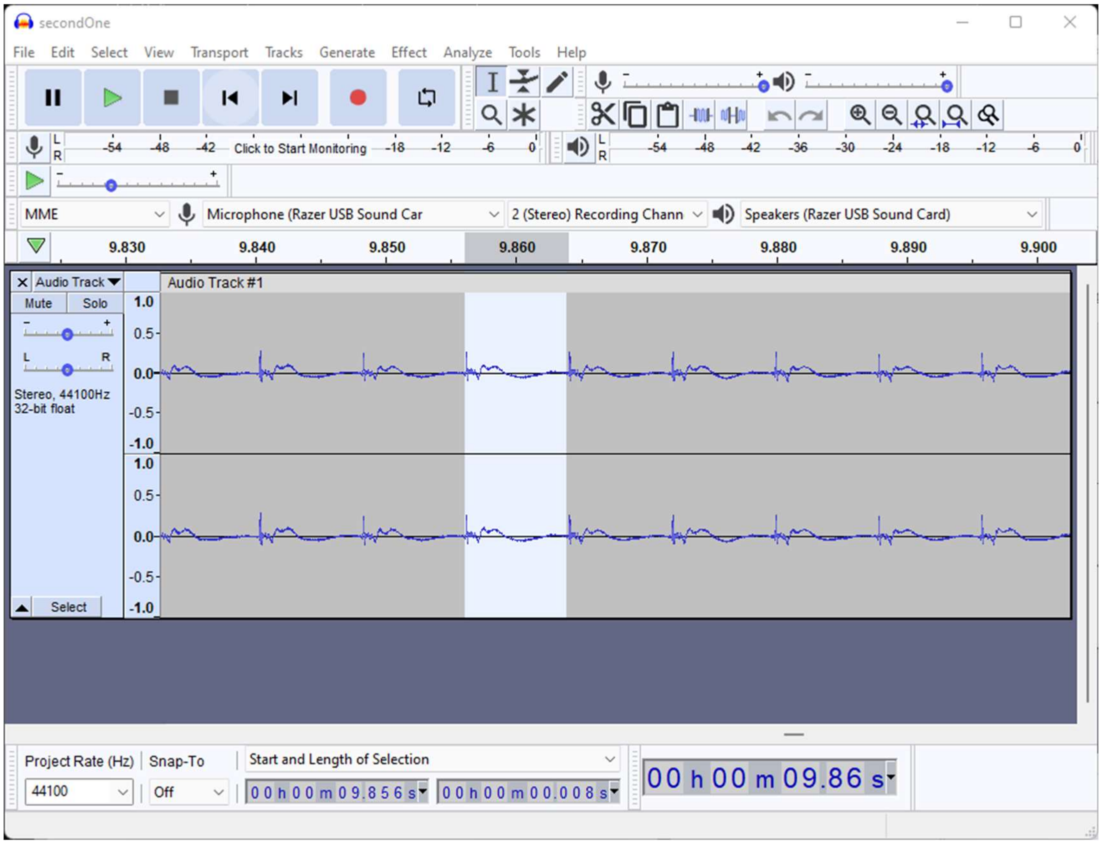

Figure 2: Recording of Motor 1 at 16.0 volts open and enlarged in Audacity

Safety

Table 3: List of potential safety hazards

Type	*Hazard*	*Measures*
Physical	Fast moving parts	Having short hair and no loose clothing during the experiment.
	Electrical leads	Make sure they do not come into contact with metal or liquids to prevent short circuits.
	Keyboard and other electronics	Be cautious around equipment and make sure there are no food/drinks around the experiment area.

Data & Observations

Table 4: Raw data from the experiment

Voltage	Current	Motor 1	Motor 2	Motor 3	Motor 4	Average

16.0 V	0.07 A	0.008s	0.007s	0.008s	0.008s	0.00775s
12.0 V	0.06 A	0.011s	0.010s	0.011s	0.011s	0.01075s
8.0 V	0.06 A	0.017s	0.015s	0.017s	0.016s	0.01625s
4.0 V	0.05 A	0.034s	0.034s	0.038s	0.038s	0.0365s
2.0 V	0.04 A	0.080s	0.076s	0.085s	0.099s	0.085s

As a bonus, I also conducted the experiment with very similar factors but decided to use motors at room temperature compared to ones that had been sitting inside a freezer for a while. The voltage was kept at 12V throughout.

Table 5: Alternate experiment with temperature as a variable:

12V	Motor 1	Motor 2	Motor 3	Motor 5
22c	0.011s	0.010s	0.011s	0.011s
-15c	0.010s	0.011s	0.011s	0.011s

This minor experiment extension shows that temperature does not affect the voltage and RPM relationship whatsoever. This is significant and shows global awareness as others around the world who may be attempting to replicate the experiment will not need to worry about varying room temperatures.

Qualitative Data:

- Motor 1 did not have anything out of the ordinary
- Motor 2 seemed to just spin a bit smoother and faster than the others
- Motor 3 had this issue where it would sometimes need to be manually started with a twist at lower voltages
- Motor 4 would often spin with a slight rattle within the metal casing at certain angles

Data Analysis

Calculating Standard Deviation

Sample standard deviation calculation for 2.0V trials

$$0.085s - 0.080s = 0.005s; 0.085s - 0.076s = 0.009s$$

$$0.085s - 0.085s = 0s; 0.085s - 0.099s = -0.014s$$

$$(0.005s)^2 + (0.009s)^2 + (0s)^2 + (-0.014s)^2 = 3.02 \times 10^{-4}s$$

$$\sqrt{\frac{3.02 \times 10^{-4}s}{4}} = 8.69 \times 10^{-3}s$$

Calculating RPM

Sample RPM calculation for 2.0V trials

$$\frac{0.085\text{s}}{60} = 706rpm$$

Experiment Analysis

Table 6: Analyzed data

Voltage	Current	Avg. rpm	Avg. times per rotation	Standard Deviation
16.0 V	0.07 A	7740 rpm	0.00775s	$4.33 \times 10^{-4}s$
12.0 V	0.06 A	5580 rpm	0.01075s	$4.33 \times 10^{-4}s$
8.0 V	0.06 A	3690 rpm	0.01625s	$8.29 \times 10^{-4}s$
4.0 V	0.05 A	1640 rpm	0.0365s	0.02
2.0 V	0.04 A	706 rpm	0.085s	$8.69 \times 10^{-3}s$

Graph 1: RPM plotted against voltage

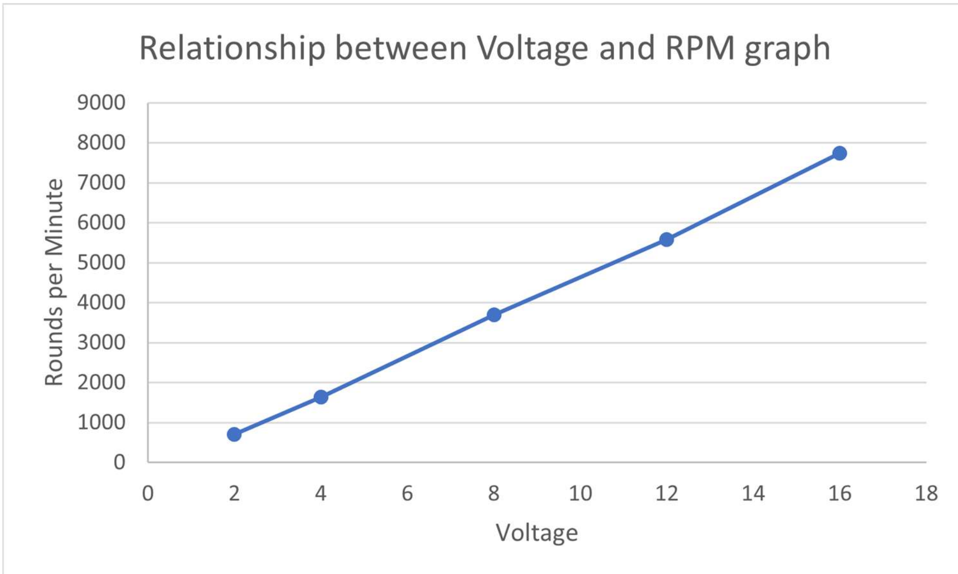

Figure 3: Graph of data made with Microsoft Excel

Theoretical Analysis

Firstly, we can easily calculate the angular speed of the motor as we have the rounds per minute.

$$\omega = rpm \times \frac{2\pi}{60}$$

Calculating Angular Speed

Sample calculation of angular speed for 2.0V trials

$$706rpm \times \frac{2\pi}{60} = 73.9rad/s$$

Next, we can work towards finding the torque of the motor. To do this, we must first rearrange a few equations.

$$P_{in} = I \times V$$

$$P_{out} = \tau \times \omega$$

$$E = \frac{P_{out}}{P_{in}}$$

$$P_{out} = P_{in} \times E$$

Thus,

$$\tau \times \omega = I \times V \times E$$

$$\tau = \frac{I \times V \times E}{\omega}$$

As we calculate the efficiency of the motor experimentally, it is recommended to find the approximate efficiency supplied by the manufacturer. Unfortunately, I was unable to locate the exact information and sought the data from a very similar looking DC motor (circuitspecialists.com). The value was 55% efficiency, which means that E will be 0.5 in all our equations.

Calculating Torque

Sample calculation of torque for 2.0V trials

$$\frac{0.04A \times 2.0V \times 0.55}{73.9\omega} = 5.95 \times 10^{-4}\tau$$

Table 7: Final analyzed data

Voltage	Current	ω (rad/s)	τ (Nm)
16.0 V	0.07 A	811	7.60×10^{-4}
12.0 V	0.06 A	584	6.78×10^{-4}
8.0 V	0.06 A	386	6.84×10^{-4}
4.0 V	0.05 A	172	6.40×10^{-4}
2.0 V	0.04 A	73.9	5.95×10^{-4}

Graph 2: voltage to torque:

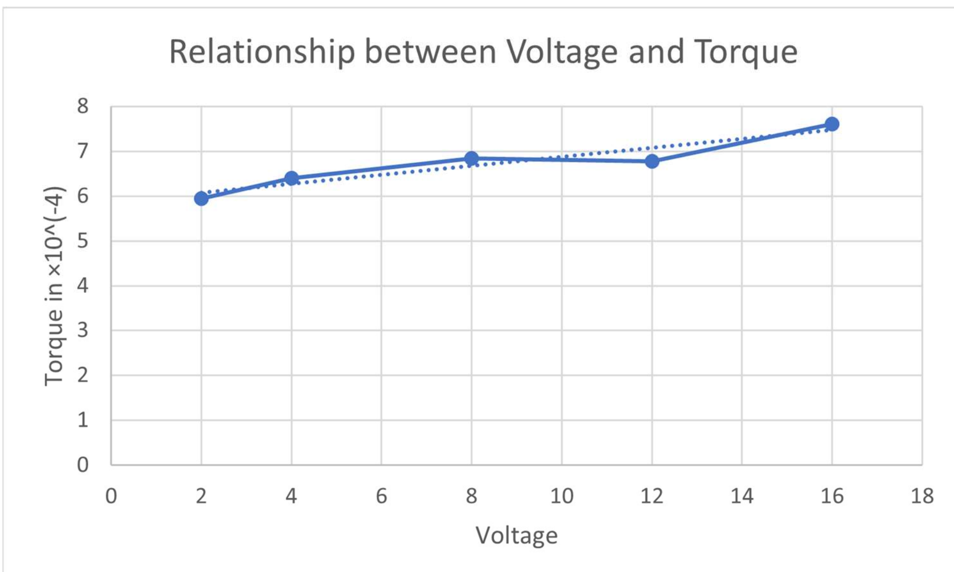

Figure 4: Graph of data made with Microsoft Excel. Note that the y axis displays numbers in that are ×10^(-4)

Evaluation

The data supports my hypothesis that the relationship between voltage and rpm is linear as can be observed from graph 1 (figure 3). However, it does not support my second part of the hypothesis where I had thought that the motors would find a peak torque value at 12.0 volts as that is the original rating for the motors.

From graph 2, the difference between varying voltages seems to have little effect on the output torque from 8 and 12 volts. There are also large jumps from 2 or 4 to 8 and 12 to 16 volts. Noting that the DC motor was originally rated as 12 volts, it is strange that there is such a performance increase from 12 to 16 volts. One reason behind this could be that it is unsustainable to run as a higher voltage would result in a higher current draw which will cause the internal coils to overheat and ultimately decrease motor life. A real-world application stemming from this discovery may be applied to electric cars as they may sometimes need a boost in torque when stuck in viscous substances like mud or when towing heavy payloads. On the other side of the spectrum, there only seemed to be a significant drop in torque when voltage dipped below 8. This is very likely due to the fact that during both the trials for 8 and 12 volts, the current draw remained a constant at 0.06 amperes. This is still significant information as it reminds us to be aware that ratings could be incorrect and lower voltages may achieve the same result at a higher efficiency. This may be going off on a slight tangent but in the world of crypto-mining, experienced miners often underclock their hardware to achieve a higher efficiency to save on energy costs. In terms of DC motors, lowering the voltage by a full third greatly increased the motor efficiency.

Conclusion

It was essential to have the current as a variable setting and to act as almost a secondary/minor dependent variable as it was still ultimately voltage that controlled how much current the motor was able to draw. In my experiment, this was achieved by setting the current knob to the max, thus only enabling the control of voltage. There are a few additional notes in the procedure that I would like to further elaborate on. It was extremely important to keep minimal additional pressure on the electrical tape tab when the motor spun as too much extra pressure increases the load on the motor and enables a higher current draw. A higher current would be an additional independent variable which would be no good for this experiment. Lastly, there is no significant uncertainty in this lab as the current and voltage readings were checked by both the built-in readings on the variable power supply but also a multimeter. The timing of the RPM is where most of the uncertainty in any physics lab is found as there is often a large degree of human error involved. However, in this lab, the audio was recorded and then the data was extrapolated to a very accurate degree which gave solid data with minimal uncertainty (see figure 2).

One point of contention in this experiment would be the usage of 55% as the approximate efficiency of the DC motors used. This is because the efficiency of small DC motors can greatly vary between 10-90%, with larger motors usually being more efficient. There was no feasible method to measure the torque of the motor as I simply lacked an apparatus that would lead me to seek out the manufacture's specifications of the motor I had. Unfortunately, I was unable to retrieve the information online as they were purchased many years ago for a project in elementary school where I was conducting experiments with solar power. This led me to use the specifications of a visually similar motor which has an efficiency rating of 55% (circuitspecialists.com). If I were to repeat this process, my top priority would be to have an accurate efficiency value as this may have greatly changed the analysis of the results.

Bibliography

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