International Baccalaureate Physics Extended Essay

Investigation of the Effects of Number of Magnets on a Homopolar Motor's Angular Acceleration

Word Count: 3979

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Introduction

The principal of how homopolar motors work is very important to understand how the electronic devices are built today or even 10 or 50 years ago. When the circuits weren't as complicated as we have today, the idea of all motors were based on the principles of homopolar motors[1]. The first electrical motor built was a homopolar motor by Michael Faraday in 1821. Since then, discovery of Faraday has become the best example for us to inspire. Still, today you will come across homopolar motors if you are studying physics or electrical engineering because they are one of the simplest direct current motors that can be done by a student who have just started to learn the subject.

Background Information

A homopolar motor is a direct current electric motor with two magnetic poles, the conductors of which always cut unidirectional lines of magnetic flux by rotating a conductor around a fixed axis so that the conductor is at right angles to a static magnetic field[2]. The name homopolar indicates that the electrical polarity of the conductor and the magnetic field act like they do in a direct current circuit. In a direct current circuit, current has one direction only, and one pole is always negative and the other pole is always positive. In an alternating current circuit, the two poles alternate between negative and positive and the direction of the current reverses periodically. That's why homopolar motors are called as simple direct current circuits.

When a wire carrying an electric current is placed in a magnetic field cross product of these 2 vectors produces Laplace Force. Following equation shows the relation between Force (N), current I (A), length of the wire L (m), magnetic field on the point B (T) and the sinus between the B vector and the wire.

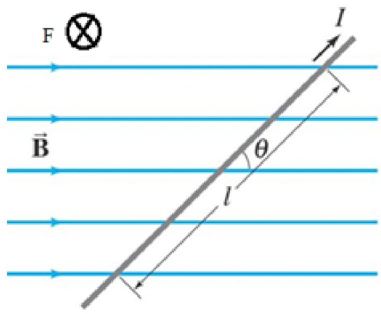


__Figure 1__ Laplace Force on a Current Carrying Wire

$$\boxed{F = BIL\sin\theta}$$

__Equation 1__ Laplace Force

The force exerted on the wire is the product of the current, length of wire inside the magnetic field and the perpendicular component of the magnetic field vector. This introduces an angle between the field and the wire.

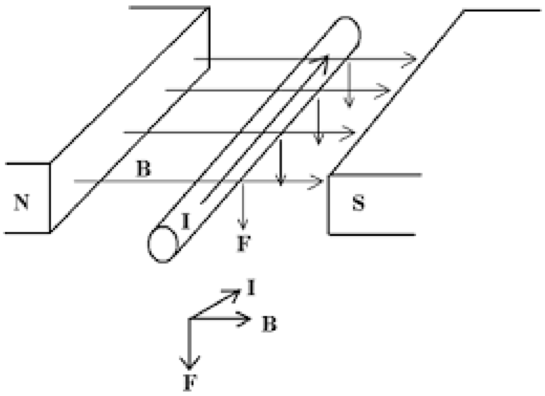


__Figure 2__ Current Carrying Wire in a Magnetic Field and exerted Laplace Force

There are two interactions between vectors; dot product and cross product. Dot product is the interactions between similar dimensions (x*x, y*y, z*z), cross product is the interactions between different dimensions (x*y, y*z, x*z, etc.). The cross product (written $\vec{a} \times \vec{b}$) has to measure a half-dozen "Cross Interactions". The calculation is done by accumulating 6 individual differences for the total[3]. The direction of the force can be simply found by the

"Right-hand Rule". The Right-hand Rule is a common method for orientation conventions for vectors in three dimensions in mathematics and physics.

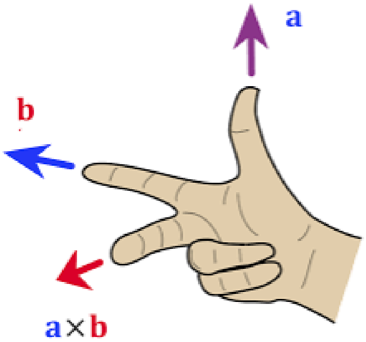


Figure 3 *Cross Product of Vectors*

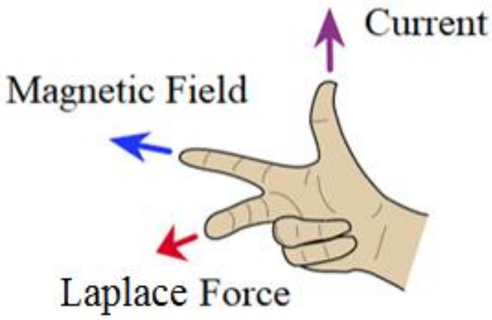


Figure 4 *Laplace Force*

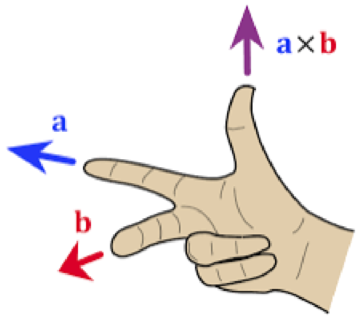


Figure 5 *Cross Product of Vectors*

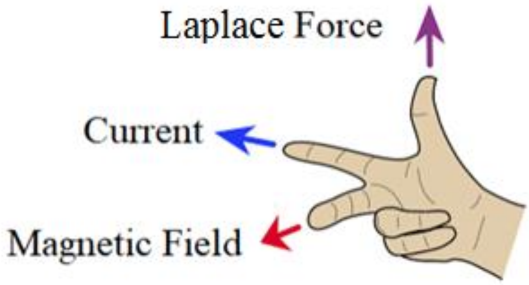


Figure 6 *Laplace Force*

[4]Because there is no right or left in space, for any direction of current and magnetic field Laplace Force is found as shown above at *Figure 4&6*. For our experiment (direction of a and b vector can be changed as shown above at *Figure 3&4*) your thumb should be parallel to the current which is the first vector. Your fore finger should be pointing the direction of magnetic field which is the second vector. Composition of two vectors are the Laplace force which is at the direction of your middle finger if you hold it as it is shown above.

We will be working on two dimensional rotational dynamics if we want to calculate the force exerted by the wire or calculate the angular acceleration of the wire. Translational dynamics has linear motion but rotational dynamics differ from translational dynamics as it has circular motion. The *Figure 7* below shows the equations will be used while we will be doing calculations on rotational dynamics.

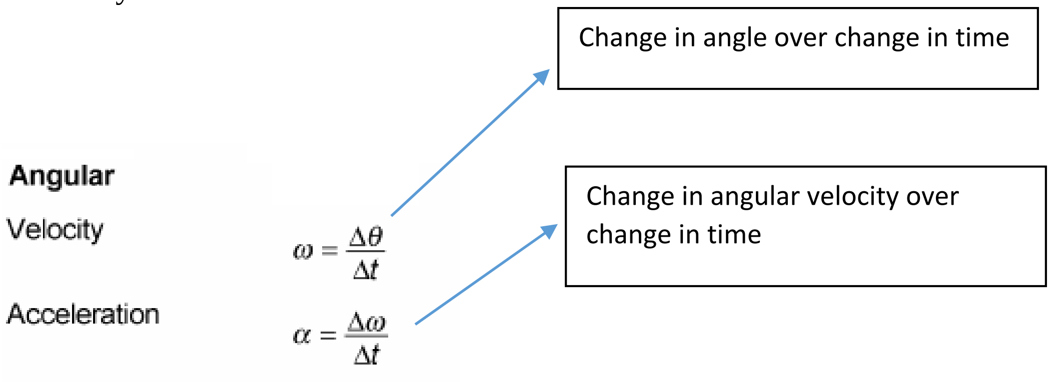
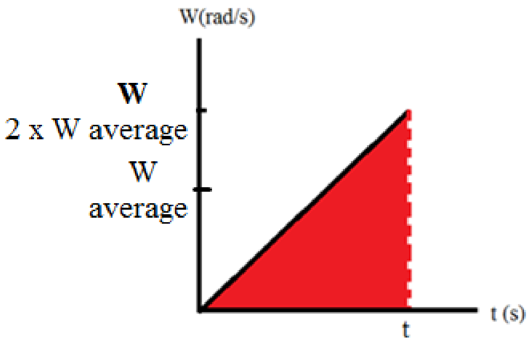


Figure 7: *Rotational Dynamics*[5]

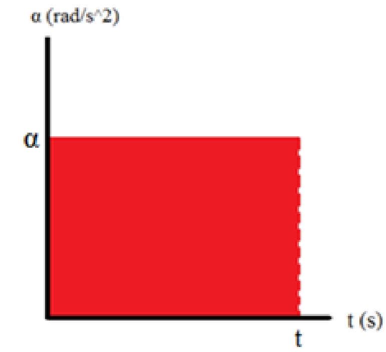
- Where θ (radian) is the angle system rotated, t (second) is the time taken for it,

ω *(radian/second)* is the angular velocity and α is the angular acceleration *(radian/second^2).*

Angular velocity shown with ω of a body is the rate of change of its angular displacement with respect to time. As shown above it is the change in angular displacement (number of revolutions) per unit time. Angular acceleration shown by α is the rate of change is angular velocity per unit time. The area under time versus angular acceleration graph gives us the rate of change of its angular velocity and the area under the time vs angular velocity graph gives us the rate of change of its angular displacement which will be used on the calculations. However, angular displacement per unit time gives the value of average angular speed which is not the value needed for the calculation of angular acceleration and we will be doubling the value found. The reason for that is as shown in Graph 1&2 below, to find angular acceleration, last speed of the motor must be divided to 60 to find average acceleration of the motor because its first angular speed is 0.



Graph 1 *Angular Speed vs Time*



Graph 2 *Angular Acceleration vs Time*

So after finding the revolutions motor completed we will be using equations below to find angular speed and acceleration:

$\theta = W \times t$	$2W = \alpha \times t$	$\alpha = (2x\theta)/t^2$

Equation 2 *Rotational Dynamics*

Equation 3 below shows how we are going to calculate the theoretical value of angular acceleration of the motor

$$\tau = I\alpha,$$

Equation 3 *Torque Equation*

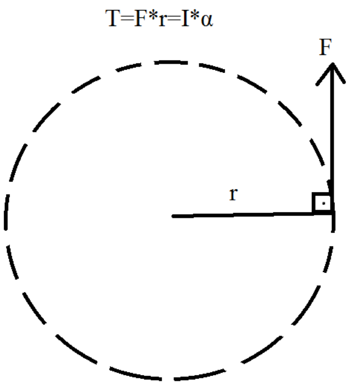


Figure 8 *Torque on a Force Exerted Object*

Where τ is the symbol for torque *(Newton x Meter)*, *I* is moment of inertia *(kilogram x meter^2)* and α is the symbol for the angular acceleration. Torque is the rotational counterpart of linear force. Moment of Inertia is the resistance of any physical object to any change in its state of motion[6]. Most of the objects have different values of inertia and it is a decisive property for object in rotational dynamics.

In the experiment we will show how the number of magnets and thus the strength of magnetic field affect the angular acceleration of the copper wire which turns around the battery and magnet. We will be adding magnets below the negative (-) pole of the battery. By collecting the necessary data we will calculate the force applied by the motor and compare experimental data and their theoretical equivalents. At the end of our experiment we will reach a conclusion about how the number of magnets affect a homopolar motor's angular acceleration?

Research Question:

How does the number of magnets affect the angular acceleration of a homopolar motor, indicated by recording the revolutions homopolar motor completed? Aim of the experiments is investigating whether the amount of magnets affect the number of revolutions completed by homopolar motor depended to magnetic field and how.

Hypothesis

In our experiment in each trial number of magnets in the setup will be increased. An increase in the number of magnets increases the magnetic field which increases the number of revolutions homopolar motor completed and its angular acceleration. Magnetic field is one of the factors affects the strength of Laplace Force. Another factor affecting the Laplace force is current which is will be stabilized in our experiment.

Experimental Variables

Independent Variable:

- Number of Magnets (Magnetic Field)

Since magnetic field is one of the factors affecting Laplace Force we will be investigating how the angular acceleration of the homopolar motor changes as we add magnets to the motor which will increase the magnetic field. Magnets will be neodymium magnets and identical for all trials. Neodymium magnets are chosen because they have the strongest magnetic field while having small volume. Magnet field produced by magnets are found by a phone application “Teslameter” measuring the magnetic field passing through a certain point. The application is used as a reliable measurement device, because while there is no magnets, it is showing the value of 60×10^{-6} Tesla which is the value stated for the certain coordinates that we are found in, at previous researches[7]. As the application shows, each of the magnets produce a magnetic field of 10^{-4} T at a distance of 4 cm which is the radius of the motor. We will be assuming magnets are producing homogenous magnetic field at a distance of 4 cm (average distance between wire and the magnets) which will be useful for our calculations because as the magnets produce non-uniform magnetic field we cannot be sure which side of the magnet producing how much magnetic field on which point.

<u>Dependent Variable:</u>

- Angular acceleration of the homopolar motor indicated by counting the revolutions motor completed from video camera

Measurement for whether angular acceleration of the motor increase or not will be determined by recording all trails to a video camera and counting the turns motor completed. The results will be compared with each other and it will be decided how magnetic field affects the angular acceleration of a homopolar motor.

<u>Controlled Variables:</u>

- **Voltage of the Batteries**

Voltage of batteries are controlled because voltage affects the current passing through copper wire. Current is a vector affecting the Laplace force and it should be stabilized. As the batteries are used on each trial their voltage decreases and new batteries should be used. 25 piece of identical 5 V are used during the experiment.

- **Length and Type of the Wire**

Length and type of the wire is kept stable during all trials because both length and type of the wire affects the resistance of the wire. As the resistance changes it changes the current passing through which will affect the amount of Laplace Force exerted on the wire.

- **Type and Strength of the Magnet**

In all trials identical neodymium magnets have been used. As the Laplace Force equation tells magnetic field has an impact on the Laplace Force and identical magnets have been used to keep magnetic field stable.

- **Temperature of the Room**

As the conductivity of metals decrease as the temperature increases all the trials have been made in 25 ℃ room temperature in order to avoid change in conductivity of metals which will affect the current.

Procedure and Steps of the Experiment

Material List& Measurement Devices

- 24 identical Batteries (1.5 V)
- Multimeter (±0.01 V, A, Ohm)
- Copper wire (150 cm) – Ruler (±0.1 cm)
- 8 neodymium magnets
- Nipper
- Soldering Tool
- Soldering Iron and solder (10 cm)
- Tape (Ribbon)
- Scissors

- Chronometer (±0.01 s)
- Slow motion video camera and tripod
- Experiment glasses and gloves

Setup

The purpose for this setup is to make a 30 cm long wire rotate around the battery successfully. First, the wire needed to be shaped and the outermost layer must be peeled so it will be suitable to twist around the battery while it is in touch with the battery and the circuit is closed. The shape used in the experiment is like a rectangular heart which is shaped with nipper as shown below in Figure 9.

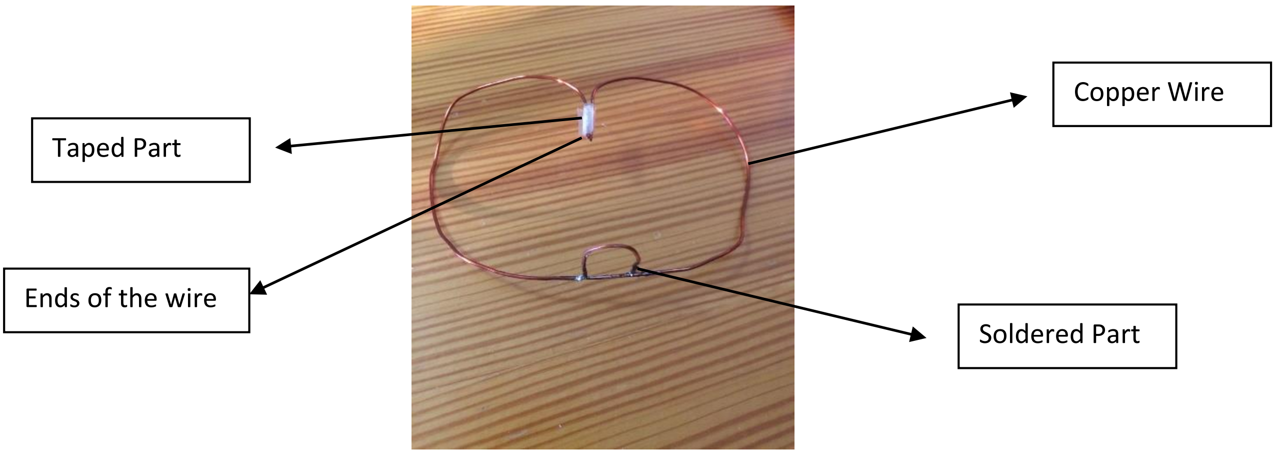


Figure 9 *Wire Used in the Experiment*

- After peeling the contact area and shaping the wire, two ends of the wire should be taped so that the current will be going through both on right and left sides of the wire which causing more force on the wire which eases the observation and data analysis, providing more data.
- While the magnets are being added, force increases and in some cases, because of increase in acceleration and velocity, the contact area levitates and circuit is left open. It means while it is not touching, force will no longer be available which will affect the results of the experiment. To make the wire touch the magnet all the time, it is

needed to solder a piece of wire at shape of a half circle. The wire should be peeled because, while the main wire is not in touch with the magnet, the soldered wire part will be.

- After doing all these, while wire' end are in touch with the battery, bottom part of the wire should be 5 mm longer than the battery so it will be able to in contact with the magnet.
- Video camera should be placed on a tripod, recording while you are placing the wire on the battery.

After all these steps and placing the battery and the magnet your setup should be similar to Figure 10 shown below.

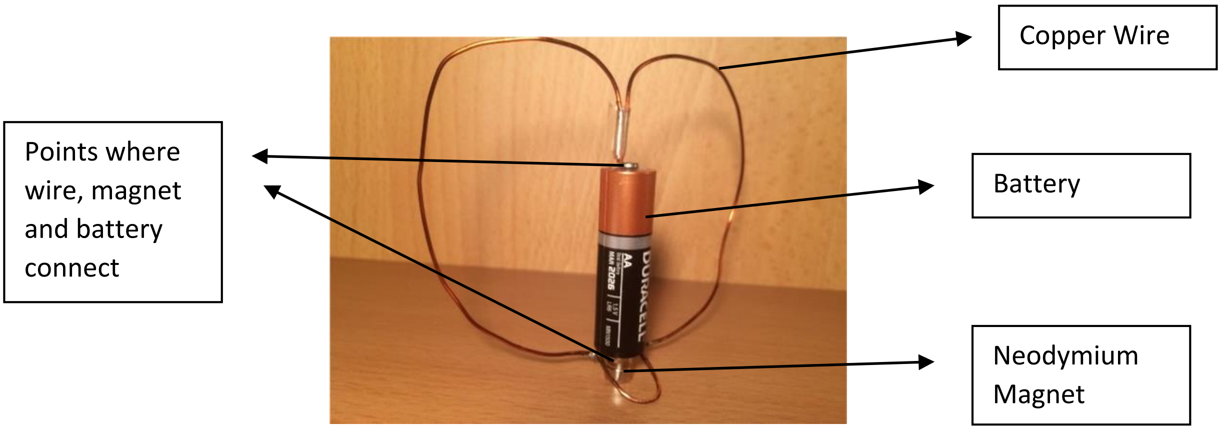


***Figure 10** Setup of the Experiment*

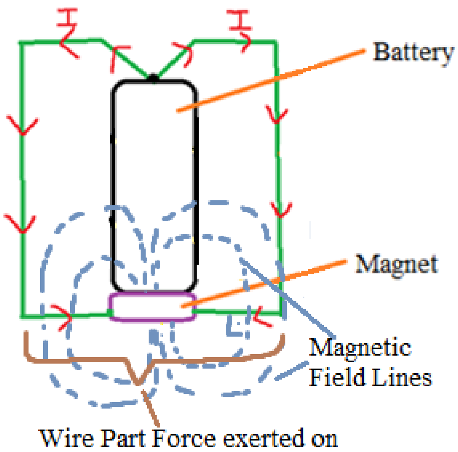


***Figure 6**Theoretical Setup of a Homopolar Motor*

Method

After preparing the necessary equipment the experiment will be done while the video camera is recording on slow motion mode. 24 batteries will be used because there will be 8 measurements which will be repeated 3 times, for all same wire will be used to keep to current stable.

Following procedure will be repeated 3 times in order to increase the reliability of the experiment;

1. Measure the resistance of the wire with the multimeter.
2. Take a new, not used battery measure its potential difference between poles because most of the time the value is different than what it says on the package of the battery and write down the value. Divide voltage to the resistance to find the current and write it down.
3. Turn the video camera on and start recording on slow motion
4. Put a single magnet under the negative pool of the battery. They should pull themselves while you are getting the magnet closer. Magnet should be on the center of the circular part of the negative pool of the battery.
5. Pass the magnet through the half circle part of the wire so the half circle won’t let it levitate while it is twisting around the battery. The setup should be standing on the magnet.
6. Immerse ends of the wire to the positive and protruding side of the battery and immediately pull your hand because it will start to twist. You should be holding chronometer on your other hand and you should start the count when motor starts to work.
7. Observe it for a minute, stop recording when the minute is over. Take the wire and put it away so battery won’t be wasted.

8. Watch the record and count how many revolutions it completed.
9. Write down the number of turns next to value of current and voltage different.
10. For every other trial, add a magnet under the last one and follow steps 2-9.
11. Sketch the graph of the values according to relevant equations to comment on.

In the end of the experiment there will be 24 values of each voltage difference, current and number of turns the wire completed. As the resistance of the wire and voltage of the batteries are found as 0.3 Ohm and 1.5 V after the trials as average, current is assumed as 5 Ampere for all trials.

Data Collected From Relevant Experiments

Number of Magnets Each of them creating B of 0.0001 Tesla	Trials	Number of Turns (±1)	The Room Temperature (C˚) (±0,1)	Current Passing Through (A) (±0,02)	Length of the Copper Wire Force Exerted on (cm) (±0,1)
1	1	68	25.0 ℃	5.00 A	10.0 cm
	2	68			
	3	69			
2	1	83	25.0 ℃	5.00 A	10.0 cm
	2	84			
	3	83			
3	1	93	25.0 ℃	5.00 A	10.0 cm
	2	92			
	3	93			
4	1	104	25.0 ℃	5.00 A	10.0 cm
	2	104			
	3	105			
5	1	110	25.0 ℃	5.00 A	10.0 cm
	2	112			
	3	112			
6	1	120	25.0 ℃	5.00 A	10.0 cm
	2	120			
	3	120			

7	1	128	25.0 ℃	5.00 A	10.0 cm
	2	127			
	3	128			
8	1	133	25.0 ℃	5.00 A	10.0 cm
	2	133			
	3	133			

Table 1 *Data Gathered from Relevant Experiments*

Uncertainties on the table are determined by the smallest digit of the measurement device. Their uncertainty is determined by the smallest digit it can measure. Because number of revolutions are counted one by one its uncertainty is the smallest value. Uncertainty of current is determined by dividing voltage to resistance, summing up their uncertainty values and the temperature is the smallest digit thermometer measure.

Data Analysis

For Experiment 1, theoretical and experimental values of angular acceleration of homopolar will be found. While doing so, mean and standard deviation will be found to comment on the values:

Mean and SD is found to be as 68.3 and 0.58 revolutions.

Calculation of Mean: (Value1+Value2+Value3)/3

$$\frac{1}{3}(68+68+69)$$

= 68.3 revolutions

Calculation of Standard Deviation:

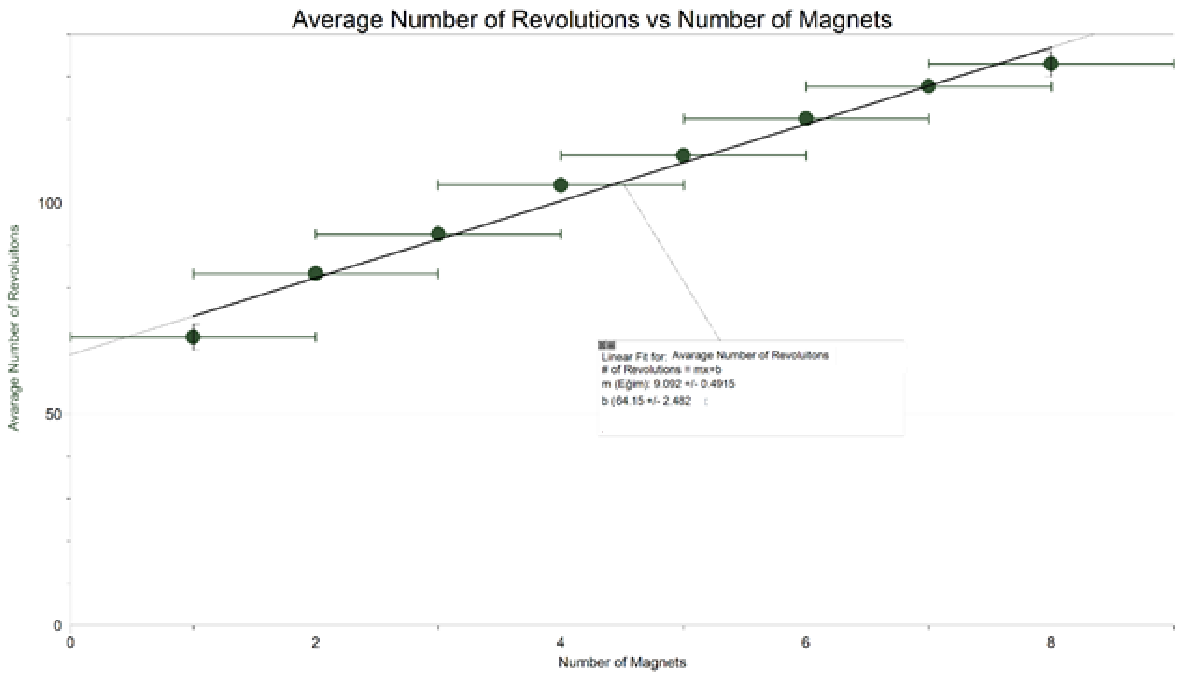
$$\text{Standard deviation} = \sqrt{\frac{\sum(\text{every individual value of marks} - \text{mean of marks})^2}{n-1}}$$

$$= \sqrt{\frac{1}{2}((68-68.3)^2+(68-68.3)^2+(69-68.3)^2)}$$

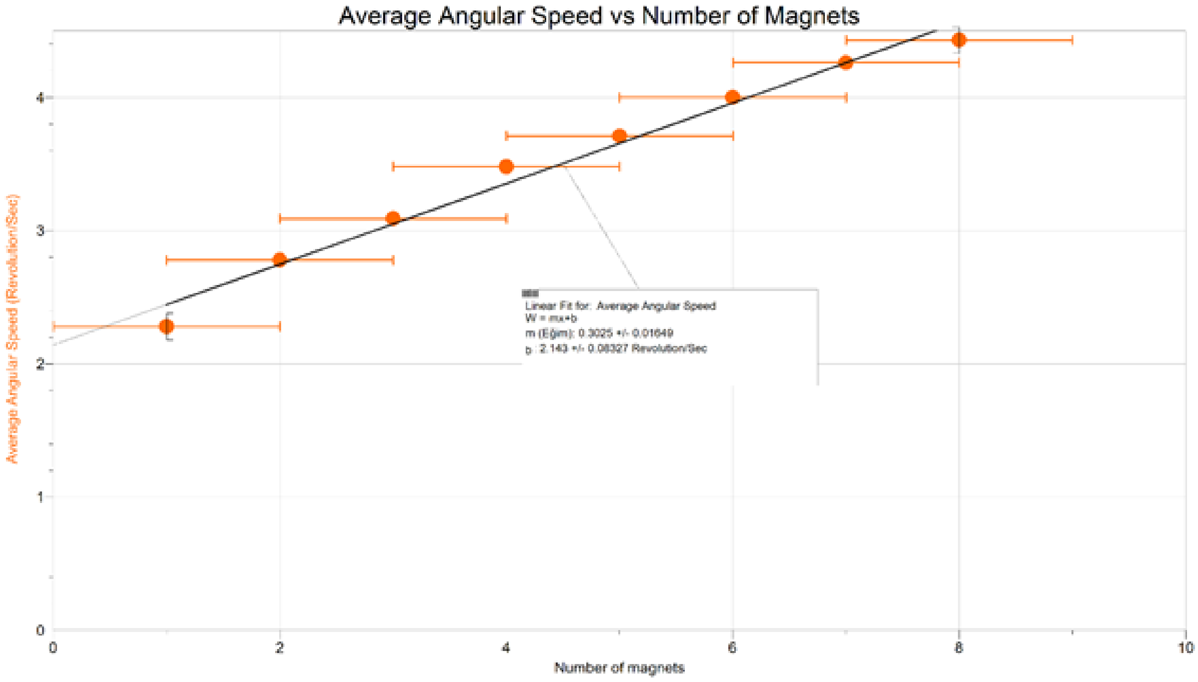
= 0.58 revolutions

Number of Magnets each creating magnetic field of 10^{-4} T at a distance of 4cm	1	2	3	4	5	6	7	8
Mean(Number of revolutions)	68.3	83.3	92.67	104.3	111.3	120	127.67	133
Data Uncertainty ((max-min)/2)	0.5	0.5	0.5	0.5	1	0	0.5	0
Standard Deviation	0.58	0.58	0.58	0.58	1.12	0	0.58	0

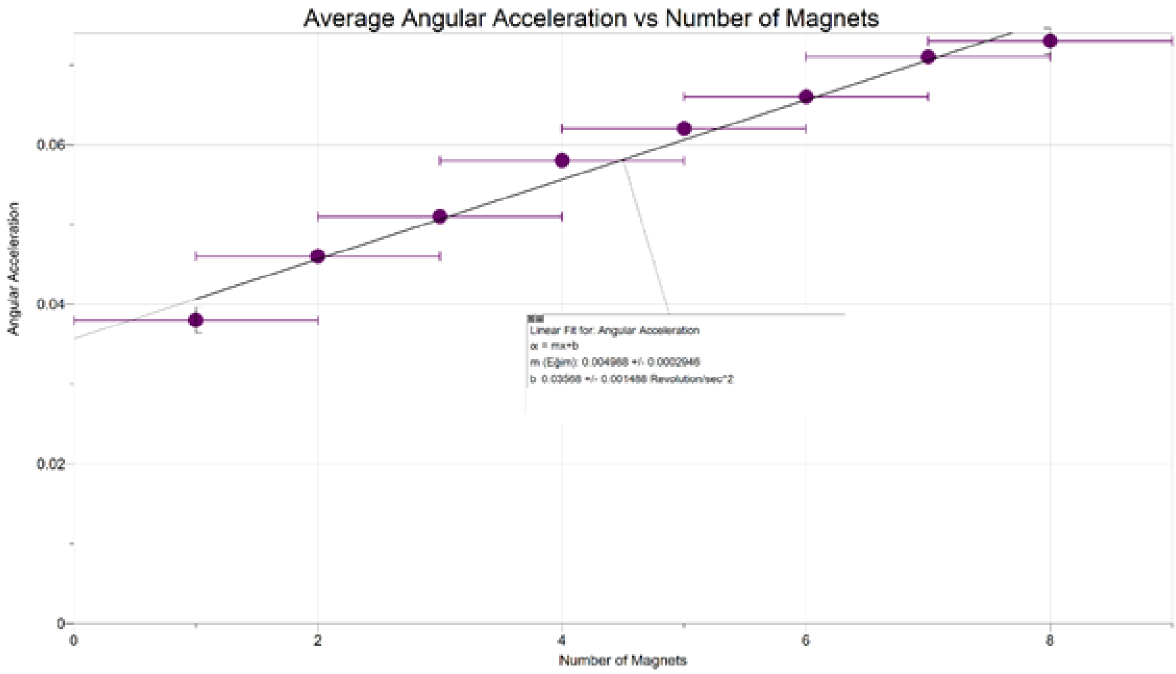
Table 2 *Data Analysis*



Graph 3 *Average Number of Revolutions vs Number of Magnets*



***Graph 4** Average Angular Speed vs Number of Magnets*



***Graph 5** Average Angular Acceleration vs Number of Magnets*

While calculating the error percentage in the experiment theoretical result should be compared to the experimental results. Summing up all the formulas given in the background information part, the formula which gives us the angular acceleration is:

Magnetic Field x Current x Length of the wire x Radius of the Motor = Mass of the wire x Radius^2 of Motor x Angular Acceleration

$= B \times I \times L \times r = m \times r^2 \times \alpha$ ($m \times r^2$ is the moment of inertia of the wire)

$= B \times I \times L = m \times r \times \alpha$

For 1 Magnet: where B= 10^{-4} Tesla, Current= 5 Ampere, Length of wire (each) = 10^{-1} m,

Mass of wire= 3×10^{-2} kg, Radius of homopolar motor = 4×10^{-2} m

$10^{-4} \times 5 \times 10^{-1} = 3 \times 10^{-2} \times 4 \times 10^{-2} \times \alpha$

$\alpha = 0.041$ revolution/s^2

Experimental results is 0.038 revolution/s^2 as it is calculated using *Equation 2;*

(2x68.3)/3600=0.038 revolution/s^2

So, our error percentage is:

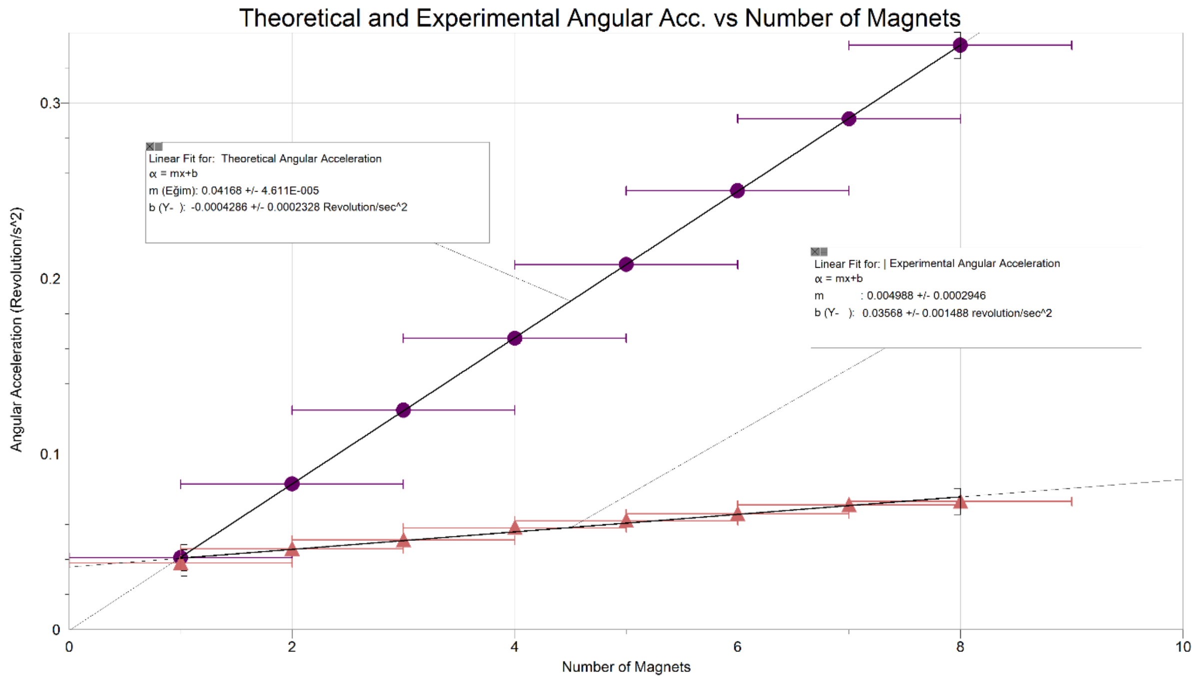
$$\% \text{ Error} = \left| \frac{\text{Theoretical Value} - \text{Experimental Value}}{\text{Theoretical Value}} \right| \text{X } 100$$

Figure 12 *Error Percentage*[8]

$$= \frac{0.041 - 0.038}{0.041} \times 100$$

= 7% error

Standard Deviation is a quantity which determines how much reliable your experiment is. If 2 standard deviation is smaller than the difference between any means, the hypothesis is supported and experiment can be assumed as reliable[9]. In our experiment mean values are between 68.3-133 revolutions and Standard Deviation values are between 0-1.15 revolutions. There are 2 data whose standard deviation is 0 which is smaller than any mean difference. So, the experiment can be assumed as reliable and data collected supports the hypothesis.



Graph 6 *Theoretical and Experimental Average Angular Acc. vs Number of Magnets*

Comparison of experimental values and theoretical values is shown at graph 6 above. As it can be seen from the graph experimental values are below the theoretical values. For Experiment 1, Percentage Error is found as 7% but graph shows that this value increase way much more on the other experiments. Both graphs are linear showing there were negligible random error or no random error on the experiment. Difference in values may be caused because of any environmental factor. For example while the experiment is being done wire is in touch with the magnet however, while we were calculating the theoretical values friction force is not included to the calculation. Theoretical value line passes through origin showing that there was systematic error on our experiment because line of experimental value does not pass through origin.

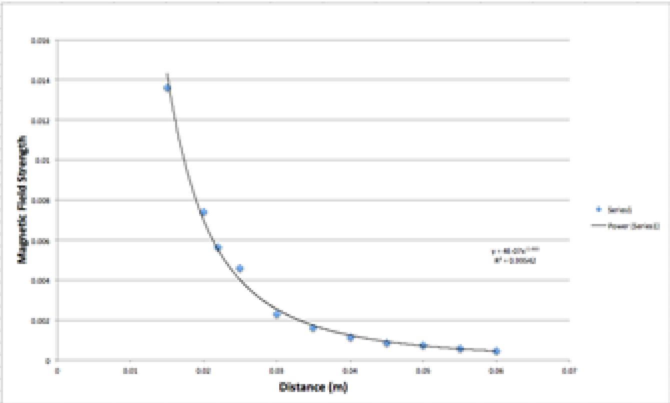
Conclusion and Evaluation:

The purpose of this essay is to analyze the data gathered from the relevant experiments designed to show how does the angular acceleration of homopolar motors change depending on the number of magnets. It is observed that number of turns that motor has finished lead us to a conclusion about how the number of magnets affect a homopolar motor’s angular acceleration.

For each experiment different numbers of magnets are used on the same homopolar motor setup made from a battery and a wire. One of the wire's end touches the battery and the other touches the magnet which is in contact with the battery. In order to make sure of the accuracy, all trials are recorded with a slow-motion camera and inspect them on the computer. 8 magnets in total are used, began with a magnet and after each trial an extra magnet is added. After counting the turns, we were able to answer our original question "How does the number of magnets effect the angular acceleration of a homopolar motor?”.

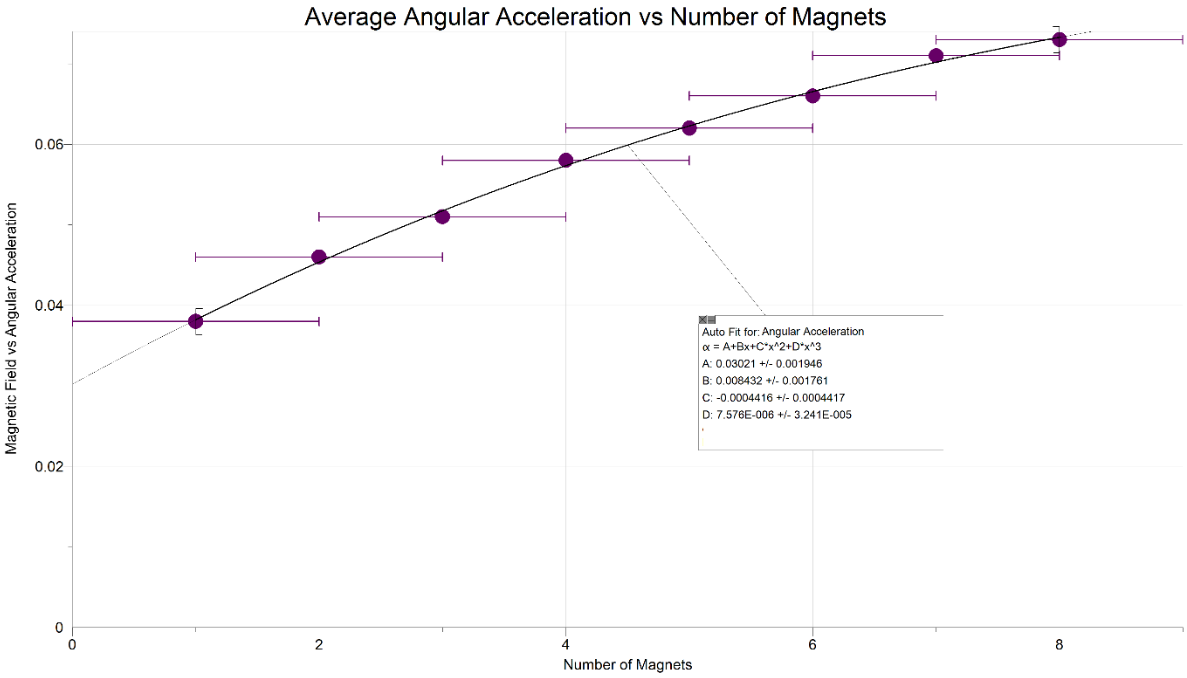
As it can be seen from the *Graph 3* average number of revolutions a motor can complete and angular acceleration of it are dependent to magnetic field. As the magnetic field increases, the number of revolutions the motor succeeds and angular acceleration of it increase. Relation between number of magnets and angular acceleration should be directly proportional as it is stated on the equations. However line does not pass through all of the points showing there is random error.

Our investigation topic is how the number of magnets in a homopolar motor affects the angular acceleration. As it can be seen from the *Graph 4 & 5,* as we add magnets to the motor, its average angular speed and acceleration increases. The change rate decreases as the number of magnets increases. It is stated that, because the line does not pass through all points there is random error but, the decrease in rate of change may be the reason line does not pass through all points. It may be caused because of the limitations stated below.



Graph 7 *Magnetic Field Strength vs Distance*[10]

As a limitation; because we are adding magnets under the other magnet, the distance between the added magnet and the wire changes. Because of this change, the Magnetic Field that magnets form in a specific area is not same with the one added above. This may be the reason why the increase rate of angular acceleration decreases as we add magnets. Because the distance between magnets and wire increases, magnetic field a single magnet producing on a specific point decreases which we assumed it doesn't. As the other researches on the topic have been done, *Graph 7* supports the idea showing how does the magnetic field on a point changes as the distance between magnets and the wire increases, which may be the reason for the graph to look like parabolic, showing the rate of change decreases instead of showing the presence of random error, as shown in the *Graph 8* below.



Graph 8 *Average Angular Acceleration vs Number of Magnets*

As the second limitation, there were uncontrolled variables during the experiment, like friction between the wire and, magnet and battery, or air friction. As it is stated above, because our system is not an ideal system, therefore there is dumping. Experimental values and theoretical values shouldn't be matched as it doesn't on the graph. The experiment is done to show the relationship between magnetic field and angular acceleration and it is difficult to succeed the whole procedure without any energy loss, reaching to theoretical value. Also the force exerted on the top wire part is neglected because as the magnetic field decreases exponential Teslameter couldn't measure any magnetic field on the point other than geomagnetic field.

As a strength, for every trial the same experimental setup is used. Batteries are changed at the beginning of every trial and this is one of the factors which avoid having random error because everything except batteries were same at all experiments and the batteries were untouched and expected to be same. As the wire is not changed including its type and length, resistance was same at all trials. Voltage of the batteries were same as well and stability of current is provided.

At the end of all trials and calculations, it was seen that the angular acceleration of motor is directly correlated with the number of magnets in the setup. It was caused by the increase in magnetic field which is depending on the number of magnets. Rate of increase in angular acceleration decreased as the number of magnets added increased. Error percentage is found as 7% showing us there were negligible random error on the first experiment however *Graph 6* showed on further experiments this value increased. As the line we plotted according the relevant experiment does not pass through origin it is a sign of systematic error which may be caused by the measuring devices that measure wrongly or deformation in the used setup.

To sum up all, the angular acceleration of homopolar motors which is determined by the revolutions it completes in a minute is depended to magnetic field. Because of the limitations, assumptions and random errors made during the experiment and calculations, a difference between theoretical and experimental value is observed.

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