Scenario A: Electromagnet Lifting

Group: 25

1 Introduction and Overview of System (Nathan Yuen)

A company hired by a mechanical engineering design firm to produce a battery powered electromagnetic lifting coupling to be integrated into their robotic crane. The magnet however did not provide enough lifting force. We as a group are contracted to redesign the coil of the electromagnet to maximize the weight lifted 100 times using only four AA or six AAA batteries. Robotic cranes that use electromagnets are very useful in the construction industry lifting heavy metals like steel pipes and plates. It creates a magnetic field generating a large pull force which lifts the metal.

To create an electromagnet, a copper wire is coiled around the plastic coil former. After that, the plastic former is placed inside the cast iron coil. At this time, it is too late to change the size of the cast iron core and the plastic former shown in Figure 1.

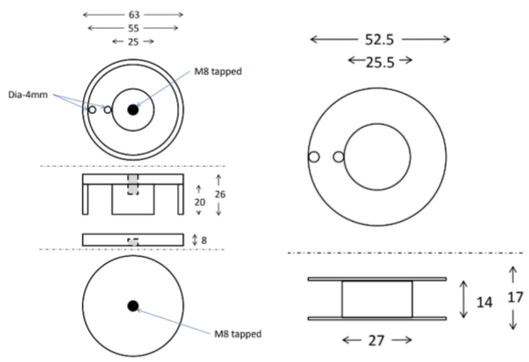

Figure 1: Cast Iron Core (Left) and Plastic Coil Former (right)

Since all the dimensions of the plastic coil former are fixed, the main factor that will decide the lifting force of the electromagnet is the diameter of our wire. We can find the largest lifting force by finding the optimum wire gauge which balances the number of turns and the resistance, while considering how long the electromagnet.

2 System Design (Nikolas Mitsokapas)

A current flowing through a wire creates a magnetic field around the wire. If the wire is coiled the magnetic field created is stronger since all the magnetic field lines pass through the coil at the same direction, [1]thus the resultant magnetic field is the superposition of all the magnetic fields produced in each turn. However, coiling the wire around a soft magnetic material, such as the ferromagnet iron, the magnetic field strength would increase even more because a ferromagnetic core has a high relative permeability, the unsaturated relative permeability used in this experiment was 980. Permeability is a measure of the ability of a material to allow a magnetic flux to flow through it. The iron core will concentrate the magnetic flux in it by changing the magnetic domain structure to all point in the same direction. However, in this experiment we attempted to reach the saturated relative permeability of cast iron by having many layers of copper wire wounded around it. At the saturation level, all the magnetic domains are point at the same direction and the magnetic flux density of the material cannot possibly increase any more. This electromagnet only functions when a current flows through the wire, the higher the current and the number of turns in the coil, the stronger the magnetic field strength. The work done to lift a weight by a certain distance is shown below. Therefore, we can calculate the maximum mass it can lift.

$$Work\ done = \Delta E = Energy\ density * \Delta Volume$$

$$= \frac{1}{2}\frac{B^2}{\mu_o} * Adx \Leftrightarrow Fdx = \frac{1}{2}\frac{B^2}{\mu_o} * Adx \Leftrightarrow F$$

$$= \frac{B^2 A}{2\mu_o}\ NF_{max} = mg \Rightarrow m_{max} = \frac{F_{max}}{g}\ kg$$

To find the maximum force the electromagnet can lift, the maximum magnetic flux density, B needs to be found, which equals: [2]$B = \mu_o \mu_r H$, $H = I * N$, where H is the magnetic field strength (A/m), I is the current (A) and N is the number of turns of coil. I and N are the dependent variables while the rest are constants, which means the maximum product of I*N will lead to the maximum force.

The voltage applied is constant, however, the resistance depends on the dimensions of the wire, and the number of turns the wire can make depends on the dimensions of the wire, therefore, our independent variable is the diameter of the wire. To determine the length of wire used by each type of wire gauge we had to approximate the saturation point of the electromagnet. Increasing the number of layers of turns of the coil will increase the magnetic flux density, however, there is a point at which all the magnetic domains of the material will point at the same direction, therefore, any other attempt to increase the magnetic flux density will not result in an increase in B. We assumed that increasing the layers of turns up to 10mm from the walls of the plastic coil will result in magnetic saturation. The resistance is proportional to the length of the wire, and inversely proportional to its cross-section area. As we increase the layers, the circumference the wire must cover increases as well, therefore, the total length of wire used up

$$L = \frac{20}{0.045} * \sum_{0}^{La-1} \left(\frac{25}{2} * 10^{-3} + 0.045 * x\right) * 2\pi$$

where La = number of layers used up.

However, the batteries used to allow this current to flow contain an internal resistance and need to be configured in a way to achieve a high current. The batteries chosen were the 6 AAA batteries in series. This would lead to the highest total resistance in internal resistances but will result in the highest voltage. This configuration was considered the highest when comparing it with the 4 AA batteries in series and in parallel. The average internal resistance of each battery was 225 mΩ. Therefore, by knowing the total internal resistance of the circuit, the total resistance of the wire and the total voltage of the batteries (9V), we can calculate the current going through the wire. We also must consider the capacity of the batteries. The electromagnet requires to lift the weights for 10 secs 100 times; therefore, the batteries need to be able to function at the required current for at least 1000 secs. The total current that requires to flow through the wires is 2.7292 A. Therefore, each battery, regardless of the configuration require to supply a current of:

For the AA batteries: $\frac{2.7292}{4} = 0.6823$ A

For the AAA batteries: $\frac{2.7292}{6} = 0.4549$ A

If the discharge of the battery is 0.5 A for the AAA battery, the battery has a capacity of about 500 mAh, as seen in the data sheet in Figure 2, meaning it will be able to function for $\frac{500}{454.9} = 1.1$ hrs = 3960 secs, therefore, the battery would last 1000 secs.

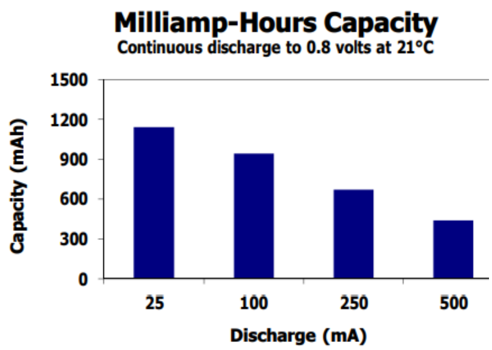

Figure 2: Capacity of AAA batteries

The AA battery, as seen in the datasheet in Figure 3, can last about 4 hours, so the AA battery has no issue with its capacity as well.

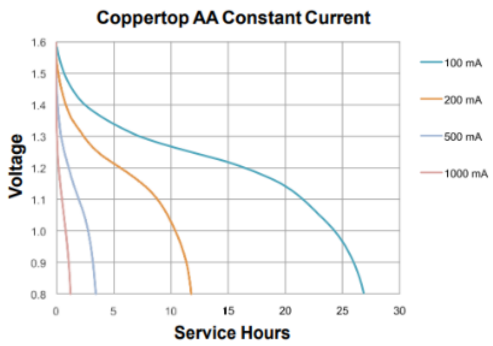

Figure 3: Service Hours vs Voltage of AA batteries

The number of turns is the number of turns in one layer multiplied by the number of layers.

By calculating I and N we can now calculate the magnetic flux density. By using MATLAB, we were able to create a model which shows the wire gauge which results in the largest maximum mass the electromagnet can lift. The model is shown Figure 3. The maximum force offered by the electromagnet is 733.807 N which is about $\frac{733.807}{9.81} = 74.802\ kg$. This is the ideal mass the electromagnet can lift, given that the cast iron has not gone through the hysteresis loop too many times.

The cast iron was magnetically saturated; therefore, the magnetic permeability reached a maximum and then decreased, therefore, the relative magnetic permeability used was less, 364.498.

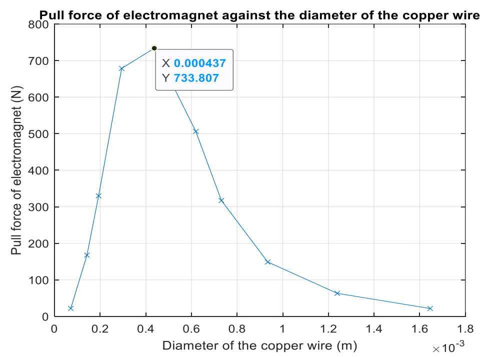

Figure 3: Diameter of Wire vs Force Model

3 Method and Results (Nathan Yuen and Nevain Dewage)

First, we will need to wind the wire around the former. The plastic coil former is placed onto a mechanism which allows it to be rotate 360° as shown in Figure 5. The nail is placed at the end to prevent the plastic coil former from falling off.

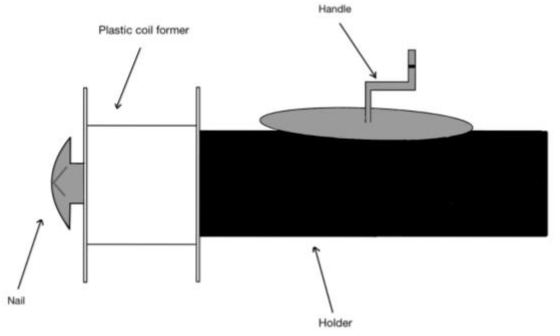

Figure 5: Winding Coil Mechanism

One end of the wire is tied at the end of the nail to keep it from falling. Then it is placed through the hole closest to the middle of the coil former. Winding the coil around the former manually is a three-person job. One person holds onto the wire while it is being coiled. The wire needs to be taut while it is wired around the coil, or else there will be gaps in between the wire and the coil former, which can reduce the number of turns. The second person will slowly spin the handle in a circle which spins the coil former, allowing the wire to go around it. The final person makes sure the wires are neatly coiled around the former. The wire is coiled around the former until it reaches the edges of the former. Since we are using a wire gauge of 27, each layer will have thirty-two coils around the former. In an ideal case, twenty-two layers could fit inside the plastic coil, however we only could fit eighteen layers. This is because after every layer, we used electrical tape to cover the entire layer. This is to ensure the wire would not unwind when starting the next layer, however the tape takes up some space inside the coil, which results in less layers in the former.

After the wire is coiled, it is placed inside the cast iron core which will create the electromagnet. The electromagnet is connected to the crane and placed above a pole carrying some weights. The wire in the electromagnet is connected to six AAA batteries in series. The batteries are initially not connected. To test the maximum lifting force of the electromagnet, the electromagnet is pulled down until it is touching the pole carrying the weights. Then the batteries are connected. This allows the magnetic field to be created. Afterwards the wheel is spun to lift the electromagnet along with the weights. If the electromagnet can lift the weights for more than 5 seconds, we can assume it is able to carry the mass of the weight. More weights added to increase the mass and the process is repeated until the electromagnet is not able to lift a certain mass. The process is shown in Figure 6.

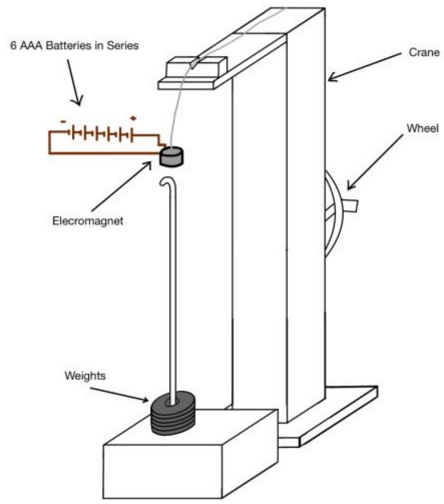

Figure 6: Electromagnet connected to the crane

The maximum weight that could be lifted one time in ideal conditions was 71kg.

4 Analysis and Conclusion (Ning Li and Nevain Dewage)

The design's actual lifting capacity is 71 kg, which is 4.2% smaller than expected. This is a result of a multiple factors. The material's internal resistance may also be overstated. In a circuit with batteries and wires that have been on for a while, some of the electrical energy will convert to thermal energy because of the greater temperature in the circuit and lower overall resistance. As a result, the circuit will produce greater current and be able to lift more weight. Also, because the number of layers of coils used was less than the calculated maximum number of layers, the actual weight is smaller than predicted.

Assuming the crane does not reduce the power transfer efficiency of the batteries, the crane will be able to perform more than 100 lifts using 6 1.5V AAA batteries, satisfying this required condition. However, comparing this to other wire gauges and battery configurations, although the battery configuration we used (AAA Series) provides the maximum weight, the wire gauge we chose lifts smaller weights than others like 16 and 18.

5 References

[1] Braza, J. "How Electromagnetic coils work", Circuit Basics, https://www.circuitbasics.com/how-electromagnetic-coils-work/
[2] "The Electromagnet", Electronic Tutorials, 2020, https://www.electronics-tutorials.ws/electromagnetism/electromagnets.html