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ELECTRICAL MACHINE ANALYSIS

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3D printed motor research

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1 Abstract

The 3D printed motor design provides a promising venture for easily built motors. However, a large degree of shortcomings also arrive through the 3D printer flaws in the EPL and due to flaws in the ABS plastic structure that render the motor difficult to build and difficult to operate unless properly modified.

2 Theory

A DC brushless motor operates by utilizing Ampere's law, stating that any current generated by an electric field also generates a magnetic field that is equally proportional.

$$\nabla X B = \underbrace{\mu_o I +}_{\text{const B field}} \quad \mu_o \epsilon \frac{\partial \Phi_e}{\partial t}$$

By placing a series of magnets around the material, we create a directional field for the permanent magnetic flux. This is called the rotor. The field equation for a bar magnet follows the magnetic dipole equations

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4 * \pi} * \left(\frac{3 * \vec{r}(\vec{r} \cdot \vec{m})}{|r^5|} - \frac{\vec{m}}{|r^3|} \right)$$

where r is the distance from the bar expressed as a vector and m is the direction of the magnetic moment of the bar.[3]

The next step is to create an opposing magnetic field using Amperes law. By inducing current, we're creating a magnetic dipole that is already inside a magnetic vector field. This then generates a torque following the equation

$$\vec{\tau} = \vec{\mu} X \vec{B}$$

. And rotates the rotor until the fields are aligned. The stator is designed to create three different magnetic dipole moments, which when placed angularly 120^o apart from each other, causes the rotor to constantly rotate.

3 Building the motor

The provided MakeSEA files for the motor were printed in the EPL using their Ultimaker 3d printing machine. The material used was ABS, a cheap plastic often used in printing. The plastic is very light weight, easily manipulated and has a tensile strength (Resistance to pressure before deforming) of 6160 - 6500 psi.
As the material was printed, a large degree of "spiderweb" like artifacts began to appear on the material. This could be a flaw in the material or in the lay out process. A large degree of the material had to be buffed using a sander so that the material could fit into place. As well, the printer created so many significant defects in what was printed that nearly half the material printed had to be discarded.

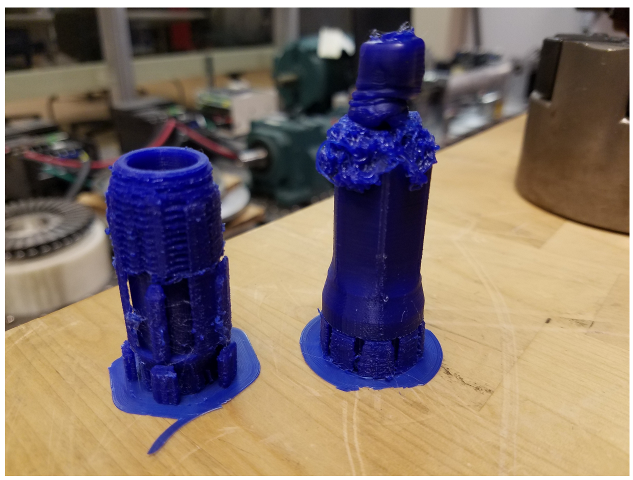

Figure 1: Physical deformities in printed material

The next step is measure the strength of the magnets provided. The magnets are 30x10x3mm neodymium magnets with a magnetic strength rating of N50. These magnets were measured using a make shift fulcrum to isolate the magnetic field from the scale. I first measured their weight and labeled the magnet with a marker. Its important to do this to prevent any imbalance in the rotor. Next I zeroed the scale, placed a stronger neodymium magnet below the previous magnet and taped them both down. This measured the *relative strength* of the magnet with respect to other magnets that are measured at the *exact same spot*.

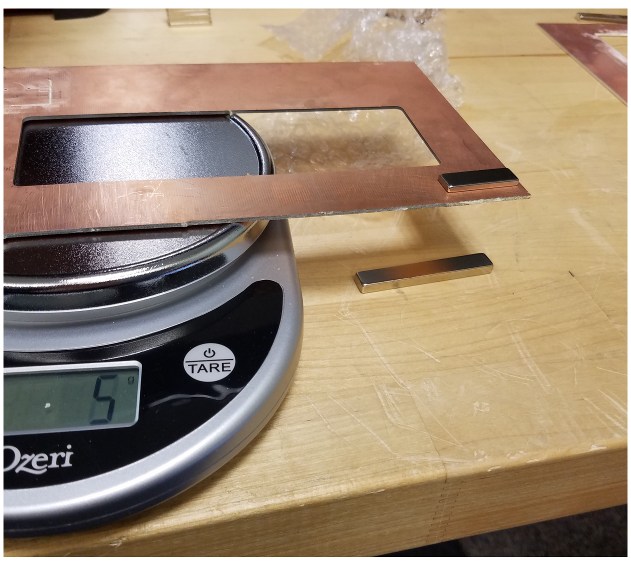

Figure 2: Magnet measurement method

The main importance of doing these measurements is to balance both the magnetic fields and the mass of the magnets so that the rotor doesn't vibrate and lose efficiency. Its important to note that the magnets are **extremely brittle** and break often. During initial testing, two magnets broke simply by removing them from other magnets.

3.1 Rotor

Once the magnets have been measured, they were attached onto the rotor so that they are evenly balanced. The rotor has small holes on one end designed for cooling, during the 3d printing process these holes are filled with small breakout tabs that can be easily removed using a screwdriver. As well, often the magnets themselves would have difficulty fitting into the ABS material. This combined with the brittle nature of the magnets means the explicit care needs to be taken when attempting to fit the magnets in. The magnets will not be able to be easily removed from the material either, so things such as polarity, strength and weight of the magnets need to be taken into account before placement.

Figure 3: Assembled rotor with magnets

3.2 Stator

The next step is to begin wiring the stator.

3.2.1 Stator 1

The first stator was wired using the first wiring diagram and the original wire provided.

The stator was wired initially using the following diagram

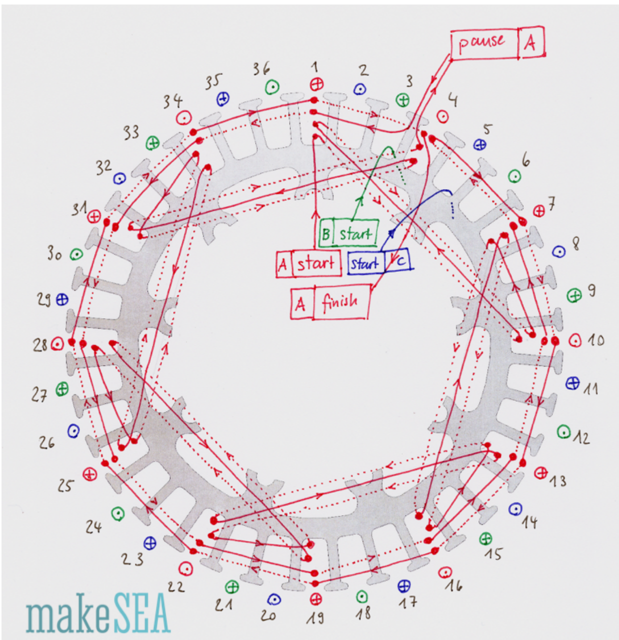

Figure 4: MakeSEA winding scheme[2]

However after carefully reading the design process again, each loop needed to be wound twice as many times as described in the actual diagram. This created a large amount of design difficulty and wasted time. The gauge provided also a significant amount of difficulty in winding. Very often, wires would pop out and needed to be placed back in. To pack the wires in, a soft surface such as a gift card needs to be used. Even after the winding was finished, the material needed to be taped to prevent the stator from unwinding. This critical information was passed on to the students building the motor later on in the quarter.

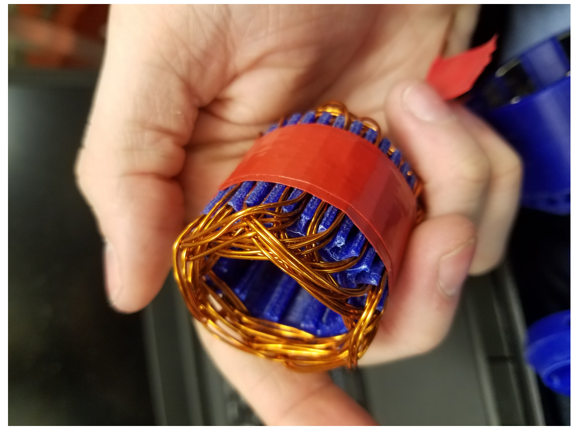

Figure 5: The first stator

The second stator followed the second design featured on the makeSEA website. This was done to avoid another costly print job that could have taken another week. As well, a higher gauge was used, which allowed for the exact wiring diagram to be followed and allowed the motor to have a close to frictionless range of motion. Like the rotor, this second stator had a significant amount of plastic waste that needed to be removed before wiring could begin.

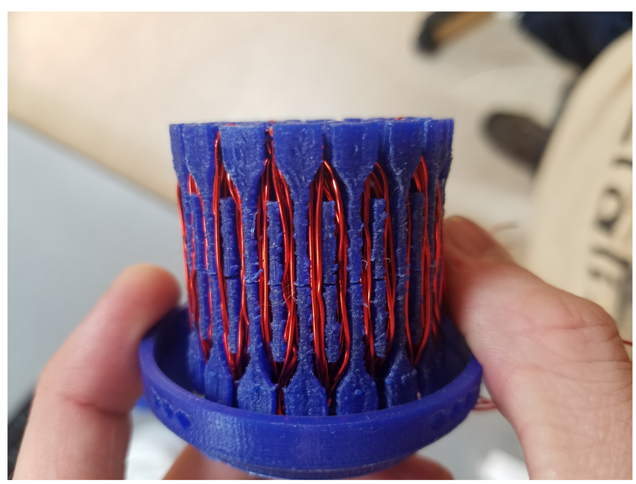

Figure 6: The second stator

The resistance of the stator was recorded after wiring and was compiled into this table.

On the makeSEA website, the measured resistance for each phase was supposed to be .04Ω, which is a tenth of what was measured.

4 The motor as a generator

The motor was tested using the second stator. During assembly of the motor as a generator, it was noted that the chuck of the motor first would not fit into its assigned place. A buffer was used to widen the hole before it could be placed. Afterwards it was noticed that the chuck needed to be screwed onto the metal rod first before being screwed into the rotor. Many students had unfortunately glued the chuck into the rotor before I noticed this, which lead them to glue the rod onto the chuck and avoid screwing the rod all together. This wasn't listed in the makeSEA project description.
Screws are not provided by makeSEA, despite it being a required piece of the equipment. To supplement this, I used a 16^{th} inch screw to hold the chuck into the rotor. The material itself (ABS) is very easily broken under stress and structural damage occurred when I drilled this screw into the hole to hold the chuck in.

Figure 7: Structural damage after placement of the chuck

Luckily this did not prevent the motor from being tested.

4.1 Testing the motor

The motor is tested by connecting the metal rod sticking out of the rotor to a drill and powering the drill. This rotates the magnets in the motor and induces electricity as the collective moment of the rotor changes with respect to the stator.

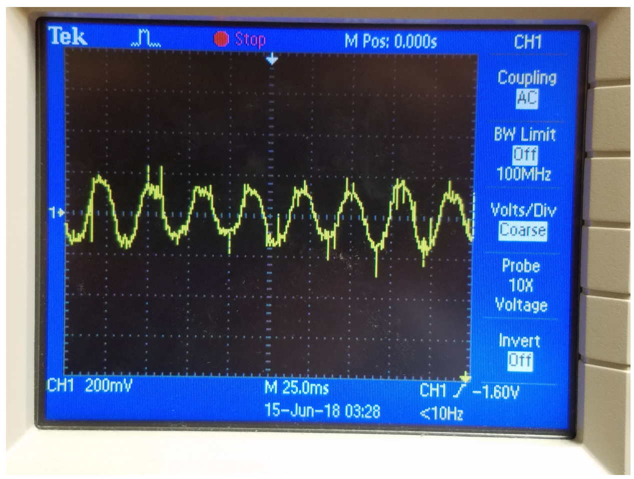

Figure 8: Voltage induced

During testing initially, it was noted that the drill creates very high frequency (100MHz to 200MHz) radiation during operation. Because I was using a high frequency cable on a high frequency oscilloscope, this made it difficult to determine what was being generated by the motor and what was generated by the drill. By switching over to a lower frequency oscilloscope that attenuates high frequency signals, I was able to avoid this issue.

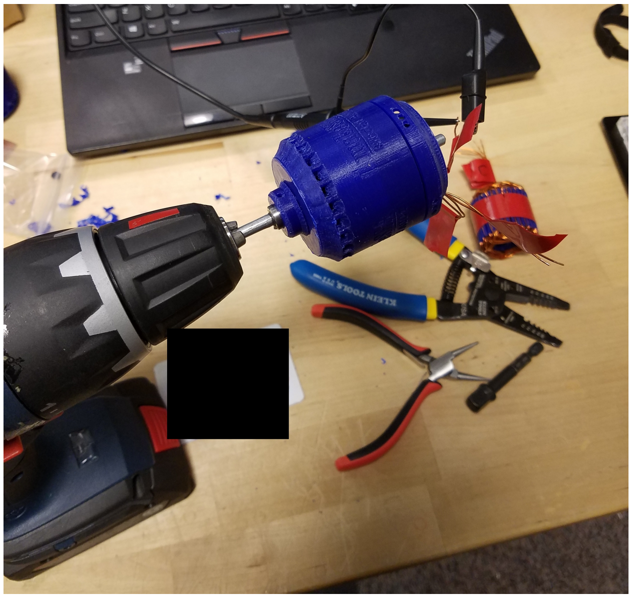

Figure 9: Motor testing apparatus

An interesting result of testing was that the induced voltage was 400mV peak to peak, which is about half what was recorded in the makeSEA measurements. This may be because of the higher resistance that was measured earlier. As well it was realized that a different, magnetically specified material, called "magnetic PLA" had been used for this motor. This wasn't available in the EPL and was therefor not chosen, this may have impeded the flux in the material.

5 Powering the motor

The motor kit came with a signal generator that was not mentioned in the documentation. When searched online, this signal generator had very little if any documentation. Basic things such as a datasheet do not exist and mysterious ports existed that made device operation very confusing. From the documentation, this generator has 3 main operations

- Manual
- Neutral
- Automatic or 'Windshield wiper'

modes. This operation was made even more confusing by the inclusion of a "S" input and output that when measured doesn't seem to output anything.

Figure 10: *Servo Consistency Master* signal generator

When powered on, the device appears to output three different signals of varying phases. However, it is difficult to measure the phases of the signals as most oscilloscopes (such as the one I own) do not have this feature.

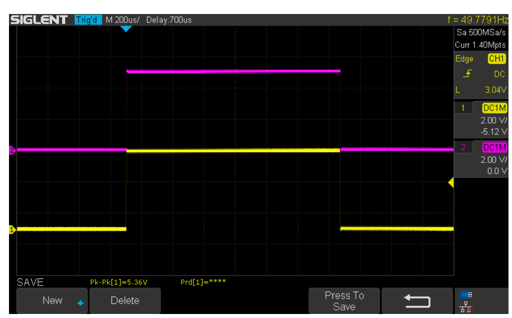

Figure 11: *Servo Consistency Master* output

This device works as a modified version

of a three phase signal generator, where two of the three phases are turned on at one single instant. During the next iteration, one of the two previous phases turns off and the phase previously off turns on. This pattern follows for the next iteration and so on. From what I can tell, this is to maximize flux inside the stator and gives a strong enough field for the rotor to rotate its moment into alignment. This contrasts with the motor as a generator, which only outputs three phase power.
A significant flaw of the signal generator is that it has a maximum output of 5V and 15mA at 50Hz, meaning that the maximum power for it to possibly provide is 75mW. This isn't anywhere near enough to move the rotor even slightly. Amplification is required if we are to use this generator properly.
This is the amplifier I designed

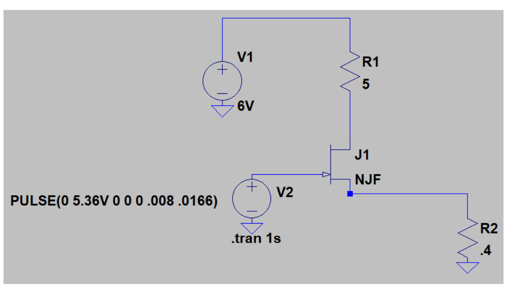

Figure 12: JFET common drain amplifier

I chose a JFET due to their easy design. If power efficiency is an important part of the amplifier, a power MOSFET can be used with little to no issue. This amplifier increases power by nearly 30dB (From 75mW to 50W) and can easily be limited with a high power variable resistor on the drain. This also allows us to control the torque of the motor.
An attempted way of powering the motor was through the 3 phase power generator provided in the power lab. However, none of the students, including myself, were successful in getting the motor to rotate. The most it did was shake violently. However, this also lead to wire oxidization and expansion in the stator due to heat.

6 Difficulties in building the motor

Its important to list every single difficulty in the motor as well as the solution to these difficulties so that future students can move past these mistakes quickly and easily.

- Printing flaws

The printer created a significant degree of headache due to the very common printing flaws associated with the printer. As well, the printer takes 3 days to print, which combined with the flaws meant that it took close to an entire week and a half to get the required parts.
Solution: Printing online may be less convenient, but this not only guarantees that the parts will be perfectly printed and on time, but also gives a wider variety of materials to use, such as Magnetic PLA.

- Brittle Magnets

The magnets contained their own issue and broke repeatedly. As well, the magnets provided were very difficult to find, the easiest way to purchase was from a seller on Ebay with a 7 day minimum wait time.
Solution: When the motor kit is purchased, it is very important to purchase extra magnets

at the same time. During measurement, separate the magnets with masking tape so that the magnets do not have direct contact. Not only does this decrease the magnetic strength among the bars, but also cushions the blow for magnets that may attempt to recombine (They will).

- Wire gauge too low

While many of the flaws in the stator size may be countered by using a better printer. Many many difficulties were encountered by wires popping out and causing large amounts of friction inside the stator.
Solution: Use a higher gauge. The trade off of higher resistance by simply moving up one single gauge higher is easily countered by the significant amount of friction loss inside the stator.

- Signal generator power output

The power output is very very small from the signal generator. This wont be able to power the motor. **Solution:** The amplifier listed above should be able to power the motor with little to no issue. It could make for an interesting assignment to ask students to make their own high power amplifier.

- Material heat vs expansion coefficient is way too high

The material used, ABS, has a very poor heat vs expansion coefficient. This coefficient (77.45μm$/^{o}$C) [1] causes the material to expand under the increase of heat as the stator is powered. During testing, I noticed that even a simple increase of around 30^{o} Celsius from room temperature caused the material to morph and deform very easily and under small amounts of pressure. **Solution:** This is the highest amount of emphasis I can put onto the idea of using a different material. ABS not only was prone to defects in printing, but also was easily deformed during use. If anything in the real world was required to use this, even a hot day would render the material permanently unusable. The material I would recommend would probably be the Magnetic PLA mentioned previously.

7 Conclusion

This motor has a fair amount of areas that could be improved. One of which would be an inventory list provided by the manufacturer, which isn't provided. Increased documentation for a variety of things provided by the website (such as assembly of the motor) also is required for a seamless building process. However, I believe that this motor once given more time can be made to work. The next step would be reprinting using a trusted website and the intended printing material, Magnetic PLA. Next I would try at least once to use the original gauge, to maximize the magnetic flux for a given voltage. Then I would test the motor using the amplified signal generated by the Servo Consistency Master. With these taken into account, the motor should rotate.
The research experience gained was forwarded to students later assembling the motor, allowing them to properly build the motor with little to no hassle. As well, solutions were created so that this research experience, although not successful, was still productive.

References

[1] https://groups.google.com/forum/m/#!starred/makerbot/4evJNxIPY2E.

[2] makesea 3d printed brushless motor v2. https://www.makesea.com/web/claimer/brushless-motor.

[3] Magnetic dipole. https://en.wikipedia.org/wiki/Magnetic_dipole, Jun 2018.