Senior Capstone Project in Green Technologies: Study of Electromagnetic Braking as Prospective Enhancement of Friction-based Automotive Braking System

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ABSTRACT

Senior engineering projects are the capstone of students' educational careers, being a proof of the skills and competencies acquired as well as an important tool to assess students' knowledge in their field of study. Capstone design courses enable students to integrate theoretical knowledge with the practical skills gained during their academic experience. Senior design projects developed by students in our department are interdisciplinary in nature and mainly address emerging or current engineering topics in areas such as manufacturing, green and renewable energies, sustainability and healthcare. The project presented in this paper addresses the need for reducing pollution by developing environmentally-friendly automotive braking systems.

Conventional frictional brakes inhibit the motion of a vehicle by converting the vehicle's kinetic energy into heat. Removing the friction between the braking elements and braking surface means the lifetime of these components would be significantly improved, which would reduce the recurring costs to the consumer over the lifetime of their vehicle and would reduce generated pollutants.[1].

This project investigated the feasibility of total or partial replacement of the frictional braking system in an automobile with a contactless electromagnetic braking system. The investigative efforts are "proof-of-concept" type. The student-led team designed and built a prototype for a frictionless electromagnetic braking system by installing computer-controlled electromagnets inside a typical drum brake assembly. When the drum rotates and passes through the magnetic field generated by the electromagnets, a Lorentz force is induced that opposes the rotation of the drum. The electromagnetic brake was compared against standards for modern vehicle braking performance to determine the feasibility of the frictionless brake's performance.

In conjunction with the electromagnetic prototype, control system and display panels were integrated into the test bench, allowing for automated control over the motor and electromagnet and automated data logging. The display panel shows the coil current, voltage, temperature along with the velocity, stopping distance, and stopping time. To ensure the coils stayed within a safe temperature, a simulation was used to determine the maximum current that could be applied before the wire would breakdown. Finally, a cost–benefit analysis was conducted to determine the economic advantages of an electromagnetic brake over a traditional friction brake. The proposed system and testing bed proved that the electromagnetic braking using eddy currents is possible and may be used to improve the existing braking systems. However, this system, as built, cannot achieve the performance required by the current braking standards.

Besides the major milestones and project design, we will describe the lessons learned and assessment of this project throughout the academic year. The educational impact of such project is assessed as well, focusing on the interdisciplinary nature of the approach.

1. Introduction

1.1. Educational Context

Capstone projects are a graduation requirement for our Engineering Technology program at Drexel University. The capstone course sequence consists of 3 quarter-based courses, 3 credits each course, that student need to complete during their senior year. During these courses, students must complete a capstone student-led project, which topic must be chosen before the fall term starts and the team of students mentored by a faculty (as team adviser). Capstone projects are assessed each term using the performance criteria based on and mapped to ABET-ETAC 1-5 (a-k) student outcomes [2, 3]. Students will present their projects formally at the end of each term in front of an evaluation panel (composed by faculty and industry specialists) and will submit a written report (each term during the academic year).

The performance outcomes used to assess student performance during the capstone project development gauges the following aspects of the projects:

1. Design of systems, components and/ or processes:
    a. Demonstrates an ability to identify system, component, or process requirements.
    b. Develops and evaluates alternative designs of engineered systems, components, or processes to minimize adverse environmental and societal impacts.
    c. Demonstrates an ability to define an optimal, realistic, and technical approach that meets design requirements in terms of technical, economic and societal criteria with realistic deadlines.
    d. Validation of the proposed solution or success of final design
2. Demonstrated ability to apply the knowledge and techniques and modern engineering tools to engineering technology problems, including assessing students' ability to apply:
    a. Knowledge of mathematics, science and/or computer programming to engineering technology problems.
    b. Knowledge of engineering and technology to engineering problems.
3. Teamwork as active participants in development and support of team objectives, sharing the work fairly and respecting teammates 'points of view.

As the project will be described below, three main pedagogical themes may be followed:

A. Students recognizing an emerging engineering need in developing a "green automotive technology". Student team enrolls in advocating for an environmentally conscious topic as a consequence of the "Global Engineer Curricula" developed within our program [4].

B. The project **interdisciplinary and complex character – development of a system approach**: project undertakes the study of a novel braking technique, using both mechanical and electrical engineering technology knowledge, combining theoretical and mathematical modeling with experimental investigation.

C. Project-based learning: exploring new knowledge and acquiring new competencies while integrating and applying the current knowledge and skills: **Learning-by-discovery teaching strategy – fostering creativity and critical thinking** from concept design brainstorming to design optimization. Student engagement in active learning and continuous professional improvement.

While the project-based learning strategy is not a new educational tool, it is important to describe how this strategy was successfully applied to the development of a student-led proposed topic. Most of the time, PBL is used with cookie-cutter type of projects, that have limited open-ended nature and have mostly pre-determined end-results. In the teacher proposed pre-designed projects, there is limited "failure" or "error" built in the project, and may be lacking any potential risk of real failure of the proposed system. In our case, students proposed their topic and they undertook a totally novel topic that might or not be feasible and with a high degree of risk that you would encounter in a graduate research project mostly rather than an undergraduate capstone project.

Below we will present the project development, from statement through validation, pointing the learning milestones achieved by the team of students.

1.2. Problem Statement

Commercial automobiles are using frictional brakes to slow and stop the motion of a vehicle by converting the kinetic energy from a system into heat. This friction between the brake element and the brake surface reduces the lifetime of both components as their surfaces are worn down, requiring them to be replaced throughout the lifetime of the vehicle. When the brake element and brake surface are worn down, they emit pollutants[1]. Figure 1 demonstrates a simplified view of a frictional brake drum. This student-led capstone project seeks to study the possibility of removing or reducing the usage of the friction-based brake by using a contactless eddy current brake. Removing the friction between the braking element and braking surface thus means the lifetime of these components would be significantly

improved which will reduce the recurring costs to the consumer throughout the lifetime of their vehicle, including reducing pollutants produced by said friction.

1.3. Background

The wheel cylinder is a piston device and is repeatedly engaged over the drive cycle. This kind of activity routinely causes wear on all the moving parts and requires continuous replacement over the lifetime of the vehicle. The lack of durability of brake shoes, wheel cylinders and all related hardware are not only inefficient but costly for the consumer. There is significant large-scale energy costs associated

Figure 1: Frictional Brake Drum

with this ongoing process of manufacturing these replacement parts for the global automobile market. The overall efficiency of a device cannot be determined without considering re-manufacturability of the device. Hydraulic brakes are no exception, so it is desirable to create a system that minimizes expensive replacement parts and eliminates the need of frictional braking system.
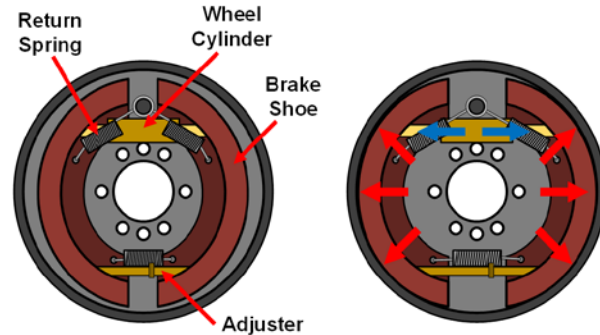
2. Research Summary

2.1. Current Technology

With regenerative brakes, the electrical energy is recovered from the kinetic energy generated while braking the vehicle and is stored in the vehicle's battery bank. Dynamic brakes allow the electrical energy to be dissipated as resistive heat when braking. Both regenerative and dynamic brakes require an electric drive to generate the electrical energy from the torque in the wheel. These braking techniques use the torque applied to the axle from the wheel to bring vehicle to a stop, which reduces the friction required for braking. The eddy current brake differs as it uses the velocity of the wheel to generate a drag force to bring the vehicle to a stop.

2.2. Patent Search

During the initial stages of the project and as part of their requirements, students engaged in researching their topic. This research included a literature survey and a patent search. They defined what would be the focus of their search: the focus was implementing eddy current braking in automobiles, as the most important aspect to consider during the patent search. While they discovered several patents within the scope of the project, all the applicable patents within this scope did not incorporate reducing the mechanical energy by acting on a rotating brake drum. The most relevant patents that were issued for similar technology integrated eddy currents in different components in the automobile. As they described in their project, patent US3601672A details a design to fine tune motor control as it relates to "sensing reflected load torque and speed and utilizing a signal derived for controlling braking of the motor.", while US6725982B layouts using eddy currents to act upon a rotating axle shaft. They concluded that the project they approached is a novel concept regarding the rest of the industry.

2.3. Standards

Another important research aspect for the capstone team was to find and explore applicable industry standards pertinent to their product. Their research concluded that the same standards and testing procedures that outline the performance requirements of traditional hydraulic brakes will be applied to the Electromagnetic Brake. They tested their competed working prototype using standard FMVSS No. 135: Light Vehicle Brakes from the U.S. Department of Transportation (standard defines the braking performance requirements of all new vehicles produced in the United States by completing traditional testing of the vehicle on a closed track) [1].

The standard requires the braking performance test to be run 10 times from a velocity of 100 km/h with at least two of the 10 stops meeting the 70-meter stopping distance requirement. The standard also

requires it to be run at different vehicle weights, but because testing was done in a laboratory setting this test could not be performed [5].

As can be seen from section 2 and 3, students followed closely not only the ABET requirements for capstone a project, their approach was very close to that of an industry like type of project: need and opportunity, current technologies, patent and standards search. The next step was concept design, including design alternatives. This phase lasted both fall and winter term and included also a design optimization phase. Once the final design was decided, they proceeded to the construction of the prototype. In addition, in the next sections, we will present the theoretical modeling of the system. While the theoretical model showed a potential success, the practical development of the system proved that a total replacement of the friction-based brakes was not possible.

2.4. Design Alternatives

It is important for students to address the need of exploring multiple design alternatives: in this phase of the project students reach their highest potential of **critical thinking:** a universe of possibilities opens. This type of **open-ended problem solving** is proven to stimulate student to brainstorm and will enable students to apply their prior knowledge, to integrate the acquired skills and competencies during their college journey in order to put in practice their ideas.

They explored different design alternatives when approaching the design of the electromagnetic braking system: from adding a stationary permanent magnet outside of the drum to adding additional stators inside the drum. What is notable is their ability to critically analyze each alternative with pros and cons, while referring to initial design requirements with realistic constraints.

The left part of Figure 2 shows a design of adding stationary permanent magnets outside of the brake drum, without contacting it, would require an additional fixture to enclose the rotating brake drum and house said magnets. This design would significantly add to the bulk of the fixture and would remove any possibility of it being a retrofitted brake. The permanent magnet design would help the performance by increasing the flux density of the field penetrating the brake drum.

Adding additional stators inside the brake drum would be a more feasible performance increase, although this design would double the current draw of the system. This design would also require a deeper brake drum or design change in the wrappings of the stator for it to be applicable. It is unknown if the performance increase on this would be greater than simply increasing the flux of a single stator by adding additional plates.

By using an aluminum brake drum, the eddy current brake would be able to be fully effective. Currently with the steel drum, the electromagnet simply attempts to align the poles with the ferromagnetic material instead of simply passing through it. Aluminum brake drums were used in classic automobiles, the low demand yields a very high price for a custom brake drum fitting the axle used for this project.

Figure 2: Permanent Magnet (Left) & Additional Stator (Right) Alternative Designs

3. Construction

In this section we present students efforts to build the system and the test bench, including all electrical and mechanical engineering aspects of it. As can be seen, they used their manufacturing topics learned in "CAD", Manufacturing Materials", CNC, and "Manufacturing Technology" courses along with knowledge acquired in "Circuits" and "Electrical Machines" courses. While building their system they started to realize the inefficiencies of their design and below are described the paths taken to overcome these issues. They have been guided the entire academic year by the advisors (authors of the paper) to have alternative plans for their system in case their initial design would not produce expected results. A continuous analysis of the failures was performed on a weekly basis, with viable plans put in place.

They used and old rear axle out of a Ford E 250 van for the test bench, with an axle of diameter of 8 inches and a depth of 3 inches, to allows for a large electromagnet which means the turn density of the solenoid can be increased to generate a larger flux density, along with a higher core surface area which will increase the magnetic flux.

For the control scheme and experimentation all 12 coils in parallel. Although inefficient, the design change allowed for a finer resolution of control and a reduced chance of systematic failure, but at the cost of higher cumulative current draw and higher sensitivity to noise.

A bank of high power relays is used to control the electromagnet and opto–isolated transistors are used to control the relays. The specifics of the control circuitry are discussed further in section 3.3.

3.1. Electromagnet

To construct the electromagnet, 18-gauge steel sheets were cut with a water jet based on the CAD design. The water jet was chosen because it has high repeatability and precision for the cut parts. Once the core pieces were cut out each plate was sprayed with a high voltage insulating spray. The spray insulates the individual steel plates from each other and helps to ensure the wire is insulated as well. The plates must be insulated from one another to reduce eddy current build up in the plates as they impede the development of the magnetic field.

Figure 3: Wrapping Process

After the preliminary testing each of the core spokes were then wrapped up to 500 turns of wire until the whole core was completed, this process can be seen in Figure 3. The thermocouples will allow for a more accurate temperature reading of the coils and the core when fully assembled than the non-contact thermometer.
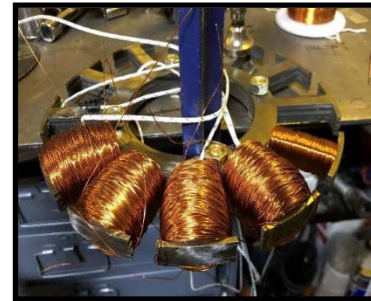
3.2. Test Bench

Since this project was going to have a large and heavy test fixture a sturdy and moveable work surface was needed: a custom test bench was built from a flat cart. The bench grinder was mounted to the test fixture, which will act as a propulsion device to spin the axle during testing and a two-piece coupler to couple the bench grinder to the axle shaft was constructed.

Figure 4: Brake Rotor Assembly

The final part of the assembly phase was to mount the electromagnet to the axle tube. This was done by welding the mounting bracket onto the axle tube then installing the electromagnet on the axle tube, with the brake rotor installed over it as shown in Figure 4.

3.3. Control System

The control system was mounted onto a piece of plexiglass that was then mounted to the test fixture. With the plexiglass mounted to the test fixture, four terminal strips for all the wires from the electromagnet were mounted to the plexiglass. A ground bus was then installed for the returns of the coil connections. Following that the relays, transistor stage, and Arduino were then mounted to the test fixture.

The signal comes into an optical isolator that is used to open and close the gate of a MOSFET. The MOSFET turns on and off the voltage supply to the relay which is used to turn on and off the current to the coils of the electromagnet. A single channel of this circuit is shown in Figure 5.

Figure 5: Single Channel of Control System

3.4. Test Panel

Due to the nature of the project, collecting reliable data was not possible without automation. A test panel was designed and built to allow for convenient and automated control of the entire test fixture. The panel allows for complete monitoring of the testing parameters along with ability to power the motor, the brake, and the control system through their respective toggle switches. The test is started by actuating the green pushbutton switch and the motor is started and begins to ramp up to speed. When the specified speed per the standard is detected, the motor is shutoff and the brake is

Figure 6: Display Panel

started automatically. The brake is then shutoff when the speed is detected to be 10 km/h or less. The performance data is logged into an SD card while the brake is active. The distance and time values are set to zero when the black pushbutton switch is pressed to allow a new test to be run. The brake can be started and stopped manually through the momentary switch.

The reason for the minimum velocity cutoff is due to the nature of capturing the velocity with the sensor. To accurately measure the velocity, the sensor needs to "hold" the program while it senses a complete period of the revolution. This is not an issue if a separate controller is used to measure the rpm.

4. Theory

4.1. Temperature

One of the ways this project is going to be simulated is by using a model to determine the temperature of the coil as a function of position, i and time, t. This lets the model act as a matrix as shown in Figure 7. Due to the self-heating of the coil, there is a temperature gradient that will develop where the outermost layers have a much lower temperature than the innermost layers, giving a parabolic curve to the temperature

$$t \begin{bmatrix} T_{i,t} & T_{i+1,t} & T_{i+2,t} & T_{i+3,t} & T_{i+n,t} \\ T_{i,t+1} & T_{i+1,t+1} & T_{i+2,t+1} & T_{i+3,t+1} & T_{i+n,t+1} \\ T_{i,t+2} & T_{i+1,t+2} & T_{i+2,t+2} & T_{i+3,t+2} & T_{i+n,t+2} \\ T_{i,t+3} & T_{i+1,t+3} & T_{i+2,t+3} & T_{i+3,t+3} & T_{i+n,t+3} \\ T_{i,t+n} & T_{i+1,t+n} & T_{i+2,t+n} & T_{i+3,t+n} & T_{i+n,t+n} \end{bmatrix}$$

i

Figure 7: Temperature Matrix

profile. The position, i, determines what layer of the coil you are calculating the temperature at. Because each layer is being heated by the adjacent layers at different rates, the temperature profile is formed. This temperature model is based off the model found in McIntosh and Ellis' model [6] with minor changes and

considerations needed to be done to incorporate it for this project's use, namely the lack of solenoid section will not be present in this design.

Stepping through the model with each subsequent layer ran at a specific time and current, a temperature profile will be able to be made to determine the maximum temperature the innermost layer will reach. This allows for simulation of different currents to be run at different amount of times and to be compared with one another to determine where thermal runaway occurs. Simulating various currents for a long enough time for the windings to approach near steady state, a maximum current can be found so long as the temperature at the highest point does not exceed the temperature ratings of the wire.

In Equation 1, T_i is the temperature of the current layer and r_i is the distance from the core of the solenoid to the start of the current layer, where the subscript i is used to denote the current layer number. "I" is the current flowing through the coil, while i is the position index (number of layers), and α is the temperature coefficient of the resistance of the wire. γ and β are constants used which are derived in Equation 4 and Equation 5. The first term in the brackets determines the heat flowing into the current layer from each adjacent layer, while the second term describes the heat generated from the current layer. The entire equation describes the temperature of the current layer per unit time.

$$[(T_{i+1} - T_i)(r_i + r_{i+1}) + (T_{i-1} - T_i)(r_i + r_{i-1})] + \gamma I^2 r_i (1 + \alpha T_i) = \beta r_i \frac{dT_i}{dt}$$

Equation 1: Temperature Model of a Solenoid by McIntosh and Ellis

Because the windings consist of more than just copper, the mean thermal conductivity must be found which varies with the thickness of the conductor, insulation, and their individual thermal conductivities. In Equation 2, Δr is the thickness of each layer as an individual, t_{Cu} is the thickness of the copper conductor, k_{Cu} is the thermal conductivity of the copper conductor, t_{enamel} is the thickness of the enamel insulation surrounding the copper conductor, k_{enamel} is the thermal conductivity of the enamel insulation. The thickness of the layer, Δr will be equal to the sum of the thickness of t_{Cu} and t_{enamel} which means that if it is desired, the mean thermal conductivity can be increased by adding a thermally conductive epoxy to the windings. The mean thermal diffusivity can be found as shown in Equation 3. This equation uses the mean thermal conductivity is k_{avg} and the heat capacity per unit volume, ρC_p.

$$k_{avg} = \frac{\Delta r}{\frac{t_{Cu}}{k_{Cu}} + \frac{t_{enamel}}{k_{enamel}}}$$

Equation 2: Mean Thermal Conductivity of the Windings

$$\kappa = \frac{k_{avg}}{\rho C_p}$$

Equation 3: Mean Thermal Diffusivity of the Windings

Since the equation has some parameters that do not vary with position or time, a constant is used to replace them to simplify the expression. This is shown in Equation 4 with γ. This constant uses the parameters Δr, as the layer thickness, R_{0l} as the resistance of the winding wire per unit length at a reference temperature, k_{avg} as the mean thermal conductivity, and t_w as the width of the wire, including insulation. The same is done in Equation 5 with β. This constant uses the parameters Δr as the layer thickness and κ as the mean thermal diffusivity.

$$\gamma = \frac{2\Delta r R_{0l}}{\rho C_p}$$

Equation 4: γ Constant used for the Temperature Model

$$\beta = \frac{2(\Delta r)^2}{\kappa}$$

Equation 5: β Constant used for the Temperature Model

4.2. Thermal Conductivity

The Mean Thermal Conductivity found in Equation 2 will not give an accurate answer if the Δr is assumed to be $t_{cu} + t_{enamel}$. Due to compounding errors in wrapping and the fact that the conductor is not stacked like a perfect square, the value of Δr should be approximated based on the physical dimensions of the windings and the number of turns, N. Figure 8 below shows the cross-sectional view of the windings to demonstrate the difference in the m-segments and i-layers, in this figure l and h are the length and the height of the windings, respectively. The total wire width, t_w, is the nominal outside diameter of the wire, including insulation. In this case it is the thickness of the copper conductor, t_{cu}, summed with the thickness of the enamel insulation, t_{enamel}. The segments per winding length, m_n, can be approximated with Equation 6 by using the total wire width, t_w, and the length of the windings, l. The number of layers, i, can be approximated with Equation 7 by using the total turns, N, and the number of segments, m. The layer thickness, d, can be approximated with Equation 8 by using the height of the windings, h, and the number of layers, i.
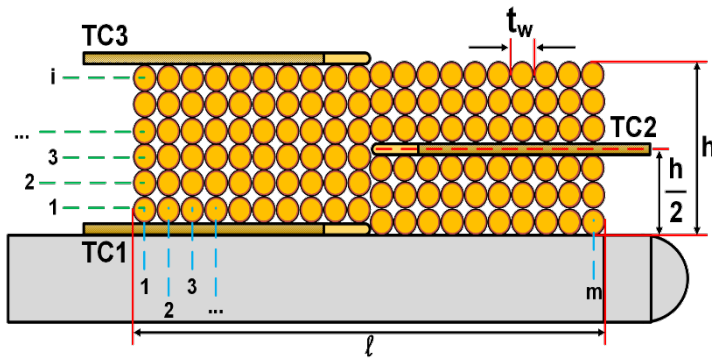
Figure 9: Measurement Approximations
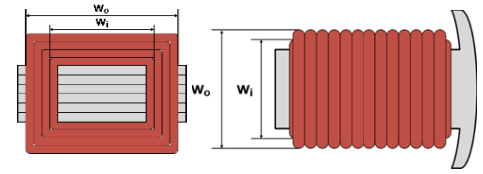
Figure 8: Cross-Sectional (Left) & Top-Down View (Right)

$$m = \frac{l}{t_w}$$

Equation 6: Segments per Winding Length Approximation

$$i = \frac{N}{m}$$

Equation 7: Layers per Winding Length Approximation

$$d = \frac{h}{i}$$

Equation 8: Layer Thickness Approximation

Because it is not possible to measure the temperature between each layer, the temperature between the inner layer at TC_2 will be compared to the outermost layers at TC_1 and TC_3 as shown in Figure 9 above. The average surface area will have to be found between the layers to treat this as linear conduction. With the 'width' of the innermost surface area and the outermost surface area measured, the average layer width can be found Equation 9 where w_o is the outer layer width, w_i is the inner layer width.

$$w_{avg} = \frac{\left(\frac{w_o + w_i}{2}\right) + (w_i + di)}{2}$$

Equation 9: Mean Layer Width

The surface area of contact between each layer will be treated as one-fourth the total surface area of the conductor as shown in Equation 10 where is w_{avg} is the previously derived average layer width. Treating the layers as stacked squares allows for a simplified equation.

$$As = \frac{\pi t_w w_{avg}}{4}$$

Equation 10: Mean Winding Surface Area

Using the datasheet for the known gauge of wire, the resistance per unit length for the wire allows for the total length of wire in the winding to be determined. With the average surface area derived, one last parameter for the thermal conduction must be derived, the heat rate. Because the measured heat rate, current multiplied by voltage, is of the entire solenoid's length this value will not be sufficient. Treating the heat rate of the layer as a percent of the total heat rate per total length, a more accurate number can be derived as shown in Equation 11 where I and V are the current and voltage and L is the total conductor length of the solenoid.

$$q = I\left(V\frac{w_{avg}}{L}\right)$$

Equation 11: Heat Rate per Segment Width

The thermal conductivity can be found by rearranging the linear heat conduction equation shown in Equation 12, where dT is the temperature difference between TC2 and either TC1 or TC3 and dx is one-half the height of the windings.

$$q = k\frac{dT}{dx}As$$

Equation 12: Linear Conduction Heat Rate

4.3. Flux Density

The output of the solenoid will be simulated by using Ampere's Circuital Law for a Solenoid, as shown in Equation 13 where B, is the magnetic flux density, µ is the permeability of the core material, N is the number of winding turns of the solenoid, I is the applied current, and l is the length of the solenoid.

$$B = \frac{\mu NI}{l}$$

Equation 13: Ampere's Circuital Law for a Solenoid

This means that the maximum magnetic flux density output of the solenoid can be found by using a core made of Carbon Steel with a permeability of 1.26×10^{-4} with 1100 turns at a maximum current of 0.577 A with a length of 0.0393 m. This gives a maximum magnetic flux density of 2.035 T.

Because a generic value for the permeability of Carbon Steel was used for this equation, to validate this model, the saturation curves of different low carbon steel were compared from the other reference data and shown in Figure 12. The graph shows that with the field strengths level that the project is going to be run at, which is the ampere-turns per unit length, the different carbon contents of the steel saturate and converge to equal one another. The graph shows that with the field strength the magnet is running at the output would be much closer to 1.55 T.
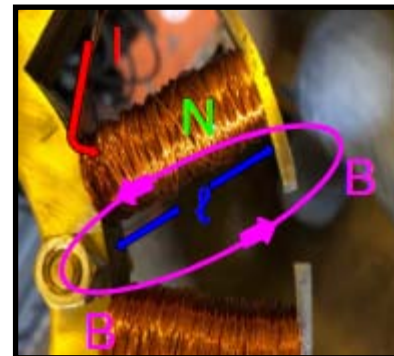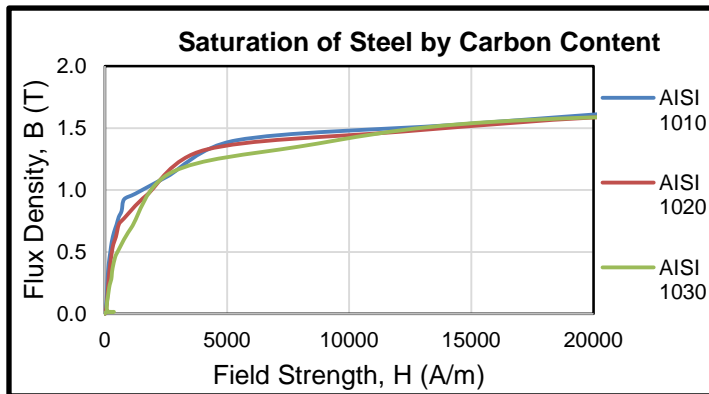

Figure 10: Ampere's Law Aid

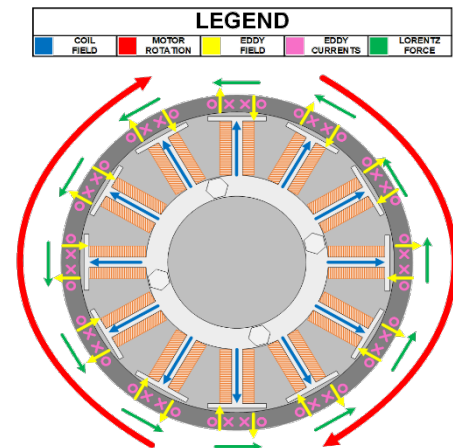Figure 11: Saturation Curves of Steel

Figure 12: Free Body Diagram of the Electromagnet

4.4. Braking

The braking of the electromagnetic brake works using the same principles of an eddy current brake. Current put into the coils produce a magnetic field that is perpendicular and penetrates the brake surface. The brake surface generates an eddy current loop due to the change in the coil magnetic field as the motor rotates. The eddy current loop will then generate a magnetic field that opposes the magnetic field that originally created the eddy current per Lenz's Law. The cross product of the eddy current and its magnetic field will induce a drag force, known as a Lorentz force, on the brake surface which will reduce the angular velocity of the wheel. The kinetic energy of the vehicle will be dissipated into heat, which consists of the Joule heating of the brake surface and the innate friction of the propulsion system and the road surface.

5. Economic Analysis, & Budget

The economic analysis for this project was based on the product not being marketable to an individual consumer. This project would produce intellectual property, and a patent that could be licensed to automotive manufacturers. The economic analysis accounts for the parts, labor to build the electromagnet device and test apparatus, labor to test the electromagnet, and machining costs as shown in Figure 13.

DESCRIPTION	ESTIMATE	QTY	TOTAL
Parts	—	—	$1,325
Electromagnet	$100.00/hr	25 hr	$2,500
Test Fixture	$100.00/hr	30 hr	$3,000
Testing	$125.00/hr	100 hr	$12,500
Machining	$150.00/hr	5 hr	$750
Total	—	—	$20,075

Figure 13: Economic Analysis

The machining costs are incurred due to the need to machine the steel plates to create and build the electromagnet core and the coupler to couple the grinder to the axle shaft. Because of the low volume of the machining, the costs to machine these pieces is much greater than it would be to machine a larger amount in a production or manufacturing setting. Also, the actual machining method that will be used is more expensive than the method that would be used in a production and manufacturing situation.

6. Life Cycle Assessment

Component	Parts	Labor	Total
Brake Pads	$50–$150	$100	$150–$250
Rotors	$200–$400	$150	$35 –$550
Calipers	$50–$100	$100	$15 –$200

Material	Cast Ion		SiC Composite	
	Ore Iron	Scrapped Steel	Aluminum	SiC
Processing	—	8.0 kWh	22.0 kWh	2.0 kWh
Reprocessing	—	5.0 kWh	1.5 kWh	—
Raw Material	12.0 kg	7.0 kg	6.0 kg Bauxite	0.3 kg
Refined Material	—	6.5 kg	1.4 kg	—
End Product	4.5 kg		1.5 kg	
Lifetime	100.00 km		200.00 km	

Figure 14: Estimated Service Cost (Left) & Life Cycle Assessment (Right)

In general, the overall efficiency of a device cannot truly be determined without considering re-manufacturability and durability of replaceable components of the device. Brake pads are no exception, so it is desirable to create a system that minimizes expensive replacement parts.

It is necessary to identify the main areas of production, use, and reprocessing of brake rotors when determining the overall cost to society. Below is an analysis conducted by The Norwegian Institute of Technology using data collected by various material producers, public administration and automobile manufacturers.

Using the industry information collected, a picture of the environmental impact becomes clear. The data for the various brake rotor construction materials includes material consumption, processing energy consumption, and reprocessing energy consumption.

7. Results

Using the automated test bed, braking performance trials were compared to the FMVSS-135 standard as well as the uninhibited control to quantify the braking improvement. The test was run 10 times and the best result is shown in Figure 15. The control distance is the average of 10 trials without any brake being applied reaching a velocity of 100km/h. This averaged the control to a stopping distance of 301 m within 13.8 s. The best of 10 trials for the brake have shown a stopping distance of 212 m within 10.3 s. This shows approximately a 30% reduction in the stopping distance. The standard does not require the brake to happen within any specified timeframe, but the time was collected to help understand how the brake is performing along with the ability to calculate the acceleration of the brake for Figure 15. When braking, the deceleration is on average 19% greater than without braking [5].
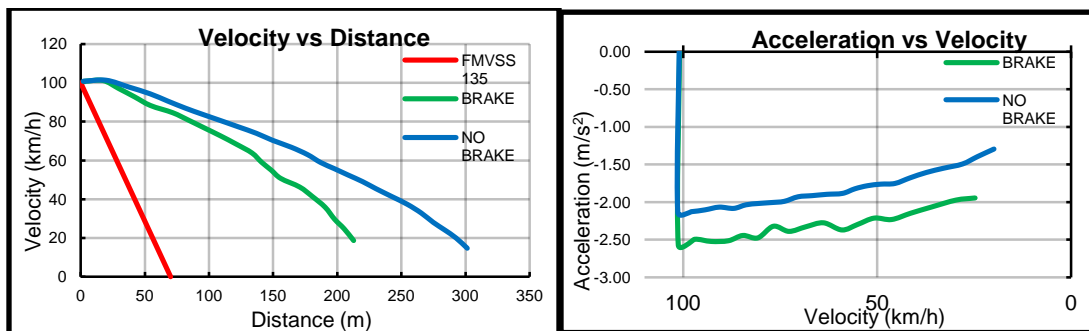

Figure 15: Stopping Distance, Best Case (Left) & Acceleration, Best Case (Right)

Using the temperature model outlined in section 4.1 a model of the solenoid temperate per layer was able to be generated given the measured parameters. The model is based off a constant current and

therefore is susceptible to a positive feedback when the temperature coefficient of the wire is taken into consideration. Without the temperature coefficient, the wire resistance is assumed to be constant regardless of the temperature. In practice the resistance of the wire would increase as the temperature rises which would cause the current to decrease, acting like a negative feedback.

The graph of the all the approximations are running 10 simulations increasing by 1000s every time, with the peak temperature marked on the final simulation. The data shows the temperature profile running at 2 A and 3 A with and without the temperature coefficient taken into consideration. The red line indicates the maximum temperature of the wire insulation.

The thermal runaway is very apparent when the feedback is introduced; Figure 16 shows the peak temperature increasing by 177% when the current is increased by 50%. Without the feedback the temperature becomes much closer to being linear, Figure 16 shows the peak temperature increasing by 98% when the current is increased by 50%.
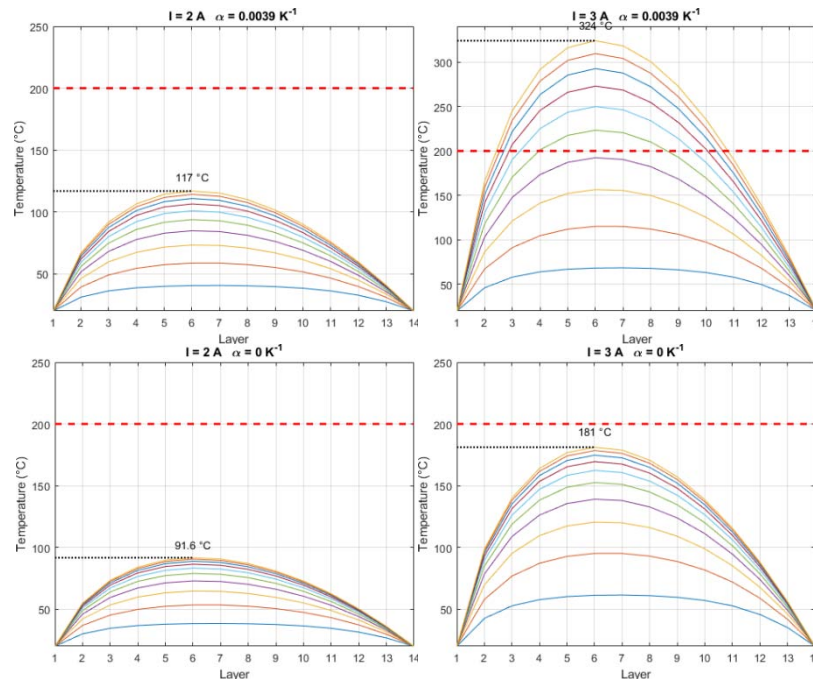
Figure 16: Approximated Layer Temperature with Feedback (Top) & Without (Bottom)

8. Conclusions of the Project

The results show a proof of concept with the original concept design. Although the performance is greatly hindered by the steel drum it can be improved by switching out the axle and using an aftermarket aluminum brake. Due to the nature of the magnetic flux attempts to align within the ferromagnetic drum instead of freely passing through it, the eddy current generated are very little, resulting in a small drag force. Unfortunately, the ramifications of this were not fully realized until the test bed was able to be completed and preliminary tests begun.

Although their project was not able to meet their initial performance expectations, students have learned much more about the theory for developing an electromagnetic brake and how to verify its performance. As part of the process they developed a fully functional test bed for monitoring and recording the performance of an electromagnet brake along with the procedures for doing so.

As can be seen, student recognized the limitations of their design and they proposed improvements that may overcome the product flaws: In Section 2.4 they presented the major design changes they would like to pursue further to compare against their current results. Increasing the flux of the electromagnet, adding a permanent magnet fixture on the outside, or using a different axle that is compatible with aftermarket aluminum brake drums would reduce help the stopping distance. Students are looking into

furthering research on this project as they filed for a provisional patent and they were engaged in VALERO automotive competition based on this senior design project.

9. Assessment of the Capstone Project

Assessment: The project scored an average score range from 4.2 to 5 for all evaluation criteria from a through k on a LIKERT scale from 1 to 5. This project represented Engineering Technology Department at Drexel University's College of Engineering Celebration of Engineering Senior Design Competition. Their major critique was related to the realistic approach of the system; however, they were praised for rigorous justification of their system flaws and inefficiencies.
All capstone projects, this one included are assessed at the end of each quarter using performance indicators stemmed and mapped to the 1 through 5 (former a-k) ABET-ETAC criteria. These performance indicators are further detailed using a Likert type scale with an equivalence to the letter grading systems as follows: a score of 5 would be an A ($\geq 90\%$); 4 would be a B (performance between 80% and 90%, and so on with 1 representing an F letter grade ($< 60\%$).

As pointed out throughout this paper, the design experience develops the students' lifelong learning skills, self-evaluations, self-discovery, and peer instruction in the design's creation, critique, and justification. Students learn to understand the manufacturer data sheets, application notes, and technical manuals and component specifications. The experience of teamwork, prototype design and test, which would be difficult to complete individually, gives the students a sense of satisfaction and accomplishment that is often lacking in many engineering courses, not including projects. Furthermore, the design experience motivates student learning and develops skills required in industry. The students were able to make satisfactory estimations and calculations of these projects. Their results reflect that they have understood well all the basic ingredients of the modeling techniques and design of the renewable energy systems. They were also very pleased with the approach used to teach them. Our experience with the incorporation of renewable energy topics in the senior project design courses demonstrated that the abstract knowledge acquired by the students during their first three years of studies was put into practice. The students in these projects gained extensive knowledge of electronics and mechanical components and their characteristics, environmental and structural constraints, separating different aspects of the project, such as generator or converter type, its parameters and characteristics, and what are the final outputs and its relationship to the load, etc. They learned, during the three-quarter senior design project course sequence to identify a problem, conduct research on a project, and compare their finding with other similar projects.
Students realized the practical challenges in integration issues and gained insight to tackle these issues in real-time, while allowing them to use problem solving skills learned in other disciplines. The key elements to success were the interdisciplinary nature of the project, the team work effort and the faculty advising and mentoring during completion of the project. The lessons learned from this type of projects lead us to believe that they are very attractive and favorable for students, leading to an increased students' engagement.

10. Acknowledgements

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