Queen's University
Kingston, Ontario, Canada

Exploration of Small-Scale MagLev Implementation and Linear Induction Motors (LIM) for Hyperloop Pod Prototypes

Undergraduate Research Dissertation (European Hyperloop Week 2023)

Author(s):
Brian Courtman, Ashley Robb, Campbell Green, Mikayla Schoner, Daniel Persaud, Dani Zhao, Seth Grief-Albert, Keaton Heisler

Contributors:
Kevin Liang

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Statement of Originality and Contribution

Following professional engineering practice, we bear the burden of proof for original work. We confirm that this work is original, and sources are cited appropriately whenever used.

Members of this paper are from the Research and Development (MagLev) team within Queen's Hyperloop: a group of design team members with engineering, sciences, and health sciences backgrounds. The main purpose of this team is to handle technical research, analysis, and developments of Hyperloop systems.

Name Full name of author/contributor	**Organization** Team or company of individual	**Content** Content contributed by author/contributor	**Write-up** Sections written by author/contributor	**Editing** Sections edited by author/contributor
Brian Courtman	Queen's Hyperloop Design Team	Electrical & Theory content	Electrical & Theory content	Electrical & Theory content
Ashley Robb	Queen's Hyperloop Design Team	Abstract	Abstract	All
Kevin Liang	Queen's Hyperloop Design Team	Abstract, Bibliography	Abstract, Bibliography	All
Campbell Green	Queen's Hyperloop Design Team	Electrical & Theory content	Electrical & Theory content	Electrical & Theory content
Mikayla Schoner	Queen's Hyperloop Design Team	Electrical & Theory content	Electrical & Theory content	Electrical & Theory content
Daniel Persaud	Queen's Hyperloop Design Team	Mechanical content	Mechanical content	Mechanical content
Dani Zhao	Queen's Hyperloop Design Team	Mechanical content	Mechanical content	Mechanical content
Seth Grief-Albert	Queen's Hyperloop Design Team	Environment & Objectives	Environment & Objectives	All
Keaton Heisler	Queen's Hyperloop Design Team	Computation & Data content	Computation & Data content	Computation & Data content

Abstract

Research Question

When developing a magnetic levitation system, there is a wide range of factors that must be considered to account for success. The system uses a linear induction motor to achieve magnetic levitation but must also incorporate data collection used for real-time analysis which is translated into the system's controls. Due to the high magnetic flux created by the linear induction motor, memory devices can be disrupted if they are not kept at a suitable distance or protected by magnetic shielding materials. The matter explored is how a linear induction motor can be implemented into a small-scale magnetic levitation hyperloop system while shielding and protecting electronic systems to accomplish data collection, system analysis and functional control of the prototype.

Overview of Motivation

The motivation for this research stems from the desire to advance safe, sustainable, and affordable high-speed transportation. The linear induction motor, computational control system and shielding necessary between each system are all crucial aspects of design and leading topics within research motivation. Without research on any of these three factors, the implementation of magnetic levitation within a hyperloop prototype would not be suitable or safe. The research completed will be implemented in the development of future Hyperloop pod prototypes designed by Queen’s Hyperloop Design Team.

Presentation of Results

As a result of the research in the topics mentioned, the team gained valuable insights that will allow further experiments and designs to be generated in the future. The result demonstrates theoretical findings of potential solutions that could cancel out magnetic fields, function as efficient linear induction motors, and computation and software that will allow other components to operate for testing. Throughout next year, the team will focus on realizing the research by constructing scalable prototypes to contest assumptions and theories.

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General

Description

Queen’s Hyperloop Design Team (QHDT) is a dynamic group of over 150 passionate undergraduate students from Queen’s University, located in Kingston, Ontario, Canada. Collaborating across diverse disciplines and faculties, our team shares a common vision to revolutionize the future of transportation, starting with our Hyperloop Pod Prototypes.

*Figure 1: **Queen’s University campus in Kingston, Ontario***

By leveraging the immense talent within the student population at Queen’s University, our multi-disciplinary team is committed to pushing the boundaries of innovation and engineering excellence. This paper serves as a testament to the collective dedication and progress made toward making Hyperloop a reality. QHDT is also a partner of the Canadian Hyperloop Conference. We are driven by a shared mission: to pioneer the future of transportation through innovation and professional excellence. With a focus on practical skill development, we empower students to excel in team management, CAD modelling, software development, part manufacturing, and forging strong industry partnerships. Guided by experienced subsystem managers, we master leading-edge programs while tackling real-world engineering challenges. QHDT thrives on a culture of ingenuity and collaboration, leveraging the exceptional talent within the Queen's community. We maximize resources by working closely with faculty advisors, collaborating with other design teams, and forming partnerships with local organizations in Kingston, Ontario, Canada. Together, we are dedicated to designing and constructing a groundbreaking hyperloop prototype that can transform the transportation landscape. Inspired by the visionary concept introduced by Elon Musk and the pioneering work of SpaceX, our hyperloop design embodies a bold vision for the future. Our goal is to revolutionize travel, dramatically reducing journey times and carbon emissions, while ensuring accessibility and affordability. Having achieved notable milestones, including our recognition as a top 21 finalist in the prestigious SpaceX Hyperloop Pod Competition, QHDT is resolute in our pursuit of excellence. We embrace the challenges and opportunities that lie ahead, in order to leave a lasting impact on the future of sustainable, high-speed transportation.

Environment & Objectives

This dissertation is conducted by the Research and Development division of the Queen's Hyperloop Design Team (QHDT) with the objective of advancing magnetic levitation principles and propulsion capacities within our Hyperloop pod. Our primary focus is on the integration of a linear induction motor (LIM) in our pod prototypes to enhance their speed and performance. This report aims to develop a technical strategy for implementing and controlling the LIM in future Hyperloop pod designs and competitions.

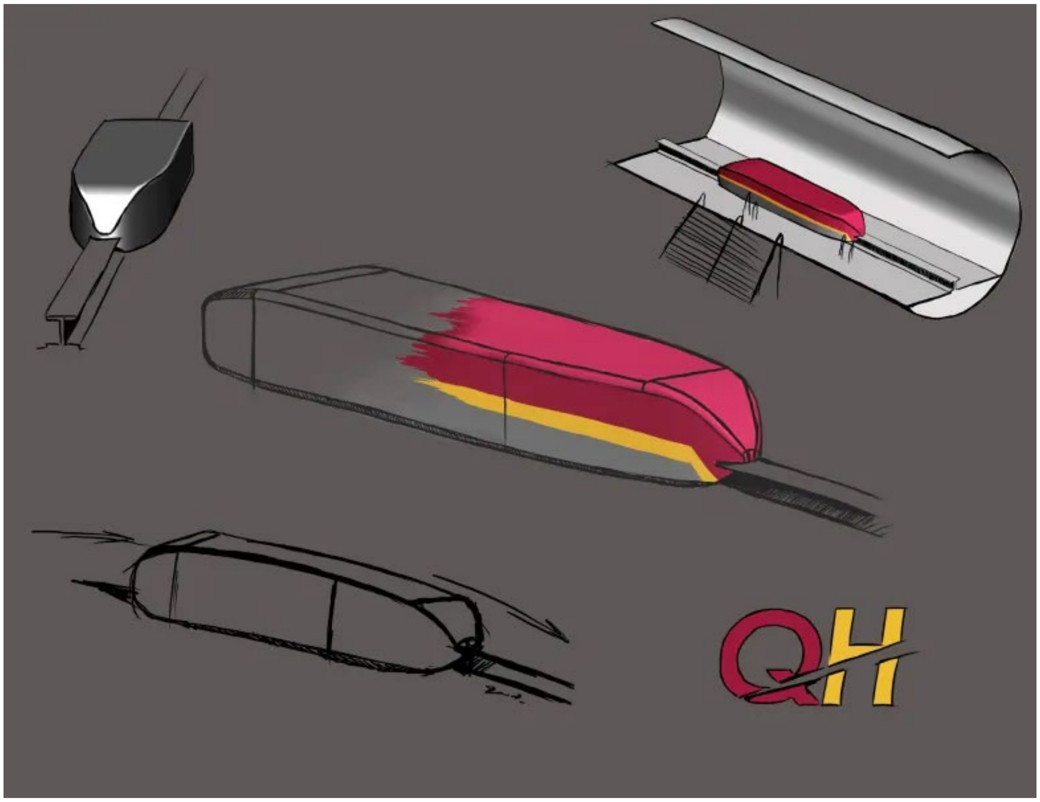


Figure 2: ***Initial design concept of Queen's Hyperloop pod***

Magnetic levitation (Maglev) and propulsion are crucial areas of interest in the Hyperloop industry due to their potential to significantly improve pod efficiency. However, practical challenges hinder the widespread use of these technologies. QHDT's Research and Development division aims to address these challenges by incrementally exploring Maglev, starting with a comprehensive understanding of the mechanical, electrical, and computational aspects involved in its development. Our initial focus is on achieving reliable control of the LIM to gather valuable operation data for future optimization. Our team is engaged in an in-depth study of existing literature and technical theories to explore various implementations of Maglev. Understanding the interaction and synergy between hardware and software systems is critical for the successful operation of Maglev technology within a Hyperloop pod. Overall, our research focuses on integrating a linear induction motor to maximize the Hyperloop's speed and performance.

Research

Introduction

Topic & Motivation: Computation and Data

The continuous evolution of Hyperloop technology has been marked by the integration of "Maglev" technology, derived from magnetic levitation. This addition introduces a new dimension to the Hyperloop system, while also presenting a set of complex challenges. Magnetic levitation enables the Hyperloop pod to hover, eliminating friction and facilitating high-speed travel. However, this levitation requires real-time measurement, precision, and management to ensure the pod's stability while in motion and at rest.

The incorporation of Maglev technology and the desire to provide a safe and enjoyable transportation option is accompanied by an increase in the amount of data that must be collected and processed within the Hyperloop system. Various sensors and measurement instruments must collect and organize data into a computation system. This system will then translate the data into precise control instructions for a linear induction motor and additional control mechanisms.

This process introduces the need to adapt quickly and dynamically to varying conditions to allow for adjustments in positioning, speed, and overall operational control. The pod may need to shift to one side to maintain balance, or slow down due to a track issue. All data must be accurately collected and computed so that control mechanisms can make split second decisions. Proper data collection is thus a requirement to ensure the safe, reliable, and efficient operation of the pod. The end goal is to offer a safe, enjoyable, and revolutionary transport option which necessitates a comprehensive computation and data system.

Topic & Motivation: Mechanical

QHDT is developing a prototype linear induction motor as proof of concept for potential integration into future competitions. LIMs are based on the generation of time-varying magnetic fields through which electromagnetic induction and repulsion could occur between two components. This generates a strong, alternating electromagnetic field (EMF) in the immediate area of the LIM. Electromagnetic field lines can be redirected using ferric materials such as steel, which can be used as a shield against EMFs.

Old forms of computer memory, including floppy disks and hard drives, store data physically by using magnets to rearrange the device's ferromagnetic materials. This data is at risk of corruption or complete loss if a high magnetic flux overpowers the existing flux value of the memory device. A strong magnetic field could also cause damage to monitoring devices. Although most modern equipment uses solid-state technology to store data, dynamic magnetic fields still pose a potential risk for data storage. Dynamic magnetic fields result in a change of magnetic flux, which is naturally resisted by conductive material. As solid-state technology stores digital data using electrical circuits, induced currents caused by dynamic magnetic fields can potentially damage or corrupt any data stored in a solid-state device. To prevent electromagnetic disruption, QHDT aims to study the effects of magnetic field strength as a function of distance and shielding material.

Topic & Motivation: Electrical and Theory

Our pursuits are driven by the integration of a linear induction motor (LIM) into our Hyperloop design, overhauling the current propulsion system. Our existing Hyperloop pod utilizes a traditional three-phase induction motor. However, the inherent limitations of this technology, including restricted rotational speed capabilities, pose significant constraints on achieving high-speed travel and necessitate complex transmission mechanisms. Recognizing the urgent need to transcend these limitations and advance the Hyperloop concept we are determined to capitalize on the potential of LIMs to propel the Hyperloop pod. Our primary objective revolves around the integration of an advanced and energy-efficient LIM, capable of serving as the primary propulsion mechanism for our Hyperloop system. The design of such a motor presents technical challenges, particularly its operation within the low-pressure environment characteristic of the Hyperloop. Our research focuses on developing an advanced linear induction motor specifically optimized for Hyperloop-like systems, capable of delivering the necessary linear thrust and surpassing the limitations of conventional propulsion mechanisms. This transformative motor will empower our Hyperloop pods with propulsion capabilities while focusing on energy efficiency and environmental sustainability.

Background Information

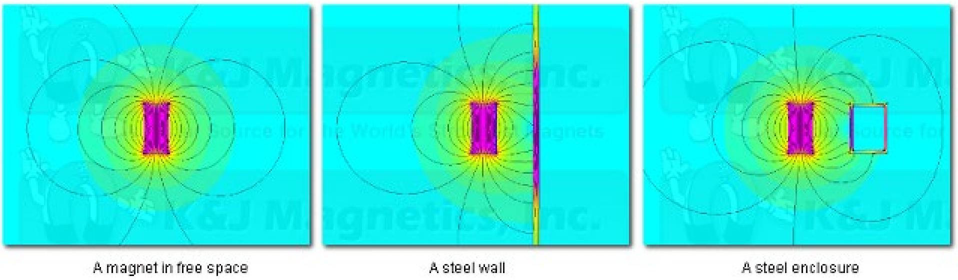
Computation and Data

The objective of the Computation and Data division is to collect and supply accurate data to the LIM and other control systems to maintain magnetic levitation at high speeds, while providing a pleasant and comfortable experience for passengers. By following these objectives, the Computation and Data team hopes to provide the Electrical and Theory team with the control inputs they need to operate and maintain safe operation of the pod.

Main challenges in achieving these objectives is processing the collected data, deciding on what needs to be adjusted autonomously, and converting the results into inputs that the LIM and other control mechanisms can read and respond to appropriately and within the required timeframe.

Mechanical

The electromagnetic field is comprised of two perpendicular osculating waves – the electric and magnetic fields. Impedance across circuits and potential damage is different between the fields and drops off with distance. The intensity of magnetization of a material that responds proportionally to an applied magnetic field is defined as permeability, expressed as $\mu = B/H$, where μ is permeability, B is the magnetic flux density of a region of space, and H is the magnetic field strength. A material with high permeability has internal dipoles easily orientated to magnetic field lines and can be thought of as the ability of a material to absorb magnetic flux; this can be visualized with Figure 3, below.



A magnet in free space

A steel wall

A steel enclosure

Figure 3: ***Interactions of magnetic field lines in free space (left), a steel wall (middle), and a steel enclosure (right)***

Magnetic field lines will seek out and follow the path of least resistance, and as such, the permeability of the shielding material must be greater than that of free space. The formula

$$\mu_r = \mu/\mu_m$$

describes relative permeability, where μ is the permeability of a material, and μ_m is the absolute permeability of a free space. The permeability of air, along with all non-magnetic materials, is $\mu_0 = 4\pi \times 10^{-7}$ H/m [1]. Saturation is the amount of flux a material can absorb until it cannot be magnetized further, even when subjected to a stronger magnetic field. High magnetic permeability and high saturation are important characteristics in magnetic shielding because they allow a material to effectively redirect magnetic fields while also maintaining its own structural integrity in the presence of strong magnetic fields.

Electrical and Theory

The theory behind the operation of a linear induction motor covers the interplay between the magnetic field and the induced eddy currents in the rotor. A linear induction motor efficiently converts electrical energy into precise linear mechanical motion. At the core of the LIM lies the stator, a vital component housing coils that generate a magnetic field. The linear induction motor revolves around the induction of eddy currents within the rotor, thereby inciting a counteractive magnetic field. This induced field exhibits a slight time delay, or slip, in relation to the stator field, instigating a distinctive speed differential. Accordingly, a magnetic force—a consequence of the enigmatic Lorentz Force—propels the rotor forward, orchestrating a harmonious synchronization with the stator field. Highlighting the interplay between electric and magnetic fields upon moving charges, the Lorentz Force constitutes the pivotal driving force within the system. The Lorentz Force exerted upon the rotor materializes as the cross-product of the induced eddy currents and the stator's magnetic flux density. This dynamic force produces torque, which subsequently introduces an impelling thrust within the linear induction motor. The provision of power to the coils is facilitated by a sophisticated 3-phase variable frequency drive (VFD). The variable frequency drive is a crucial component for controlling the speed and optimizing the performance of a linear induction motor. It allows precise adjustment of the motor's frequency and voltage, enabling versatile speed control for different applications. The VFD utilizes advanced power electronics techniques to provide variable frequency and voltage output, resulting in efficient motor performance, energy savings, and operational flexibility. This combination of LIM and VFD is particularly suitable for applications requiring precise speed and torque control, which is especially relevant in Hyperloop transportation systems.

In the pursuit of a sustainable and clean-energy future, one of the key challenges faced is the transportation of both people and cargo across long distances while minimizing reliance on fossil fuels. The linear induction motor utilizes contactless magnetic propulsion, where the generation of a moving magnetic field induces eddy currents within a conducting track surface. Operating without physical contact, this magnetic propulsion system generates a translating magnetic field that induces eddy currents within a conducting track surface. During synchronous operation, the resulting opposing magnetic fields produce a thrust force. By eliminating the need for physical contact, this technology minimizes friction, leading to improved energy efficiency. Additionally, the application of the LIM holds promise for enhanced speed and operational efficiency. QHDT aims to sustainably optimize the implementation of the LIM within our pod. Other areas of investigation include methods to reduce the strength of a magnetic field within specific regions, as well as methods to eliminate the induced current caused by oscillating magnetic fields. Understanding these phenomena is crucial for ensuring the efficient operation of our Hyperloop pod, as excessively induced currents can lead to inefficiencies, data loss, and malfunctions. By researching extensively, our team aimed to acquire a comprehensive understanding of electromagnetism as it relates to our own unique Hyperloop pod.

Methodology

Computation and Data

When approaching how exactly these controls would be modelled, there were two specific paths we identified. Using Model Predictive Control or Proportional Integral Derivative (PID) Control. We began to work in conjunction with the Electrical and Theory team to identify how exactly the Linear Induction Motor is controlled, and how we could control it using our collected data. This was completed using several published papers on both MPC and PID, along with manuals and user guides for our own VFD.

Mechanical

The mechanical team is primarily focused on paper research and familiarization with the concepts of electromagnetism as they pertain to the Hyperloop pod. Research is split into two primary topics: methods of reducing the strength of a magnetic field in some regions of space, and methods of eliminating the induced current caused by oscillating magnetic fields. The overarching goal is to gain a broad understanding of each topic to develop a tailored solution for QHDT’s unique pod.

Electrical and Theory

The motor is a single LIM that is mounted top-down on the track. This configuration was chosen due to this project's purpose being to familiarize the team with LIM construction and the processes and to learn for the future. In the future, two motors will be used, one on each side of the track. This configuration is ideal as not only does it increase total propulsion but also the efficiency of the motors. When two stators are used on either side of the rotor, the magnetic fields are pulled tighter, reducing the path length, and increasing the magnetic field strength.

Motor Design

There are no size constraints for this motor as the motor will not be mounted in a pod for testing. All other specifications were made due to cost, functionality of the motor, and time constraints.

Core design

The core design includes 9 poles to house the coils as an increase in poles results in a smoother power delivery. The reason for this is that the stator field is ideally meant to look like a traveling sine wave. With each pole added to the motor, the stator field looks like a smoother sine wave. Each pole is deep enough to house 2 coils in a non-salient pole configuration.

In a motor a significant area of efficiency loss is in induced eddy currents in the stator. When a ferromagnetic material is under the effect of a varying magnetic field, eddy currents are induced in that material. Eddy currents flowing through the stator can lead to build ups in current and heat generated by the current. An effective method to reduce eddy currents in the stator of a motor is the method of 'laminating' the core. This is done by separating the stator into small slices and insulating the slices from one another. This process reduces the magnitude of the induced eddy currents in the stator, greatly increasing power efficiency and avoiding overheating.

The core is made up of 40 separate slices of low-carbon steel, each 3.175mm thick to form a 127mm thick stator. Each slice is electrically insulated with a spray enamel to ensure that there is no eddy current leakage. In this project, the slices are held together by two bolts that are passed through cutouts in the core.

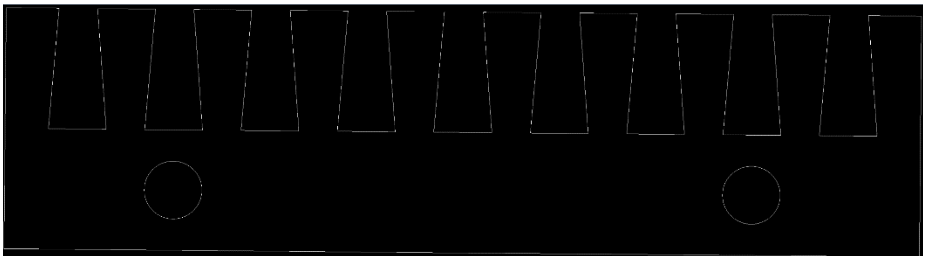


*Figure 4: **Front view of the core design, note the cuts are shaped to hold wires going through them***

Stator windings

There are 9 total windings in the stator of the motor, with each winding having the approximate dimensions of a 16x6.5 cm rectangle. 9000 feet of 30-gauge copper magnet wiring is used in the winding process, leaving each winding with approximately 650 wire strands and a cross section of ~33mm^2. The windings will be individually wrapped in insulation paper, to prevent any friction or interference between the windings and the core. In the future, a more efficient solution would be to have the windings custom made to a specified cross section. The non-salient pole configuration can be seen in Figure 5.

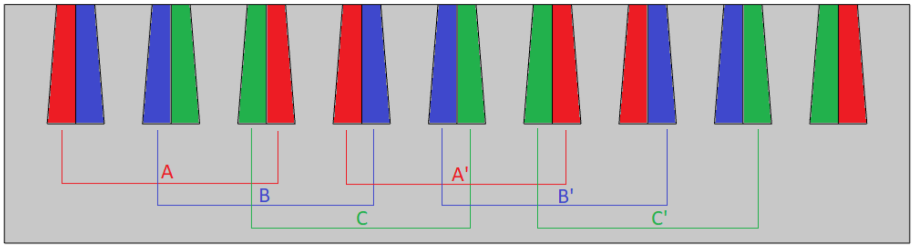


Figure 5 – Winding diagram showing the non-salient pole configuration of the LIM design. Phases A, B, and C are offset by 120°, with A', B', and C' indicating the reverse current windings.

Variable Frequency Drive

To power and control the LIM, a three phase VFD is required. The VFD, or inverter, converts the single-phase input from a voltage source into a three-phase alternating current output which are all 120 degrees out of phase. Each output phase will be powering a separate set of coils in the motor, producing a varying stator field. The phases being 120 degrees out of phase ensures that this varying field will resemble a traveling sine wave. The typical configuration of a three-phase power output can be seen in the figure below.

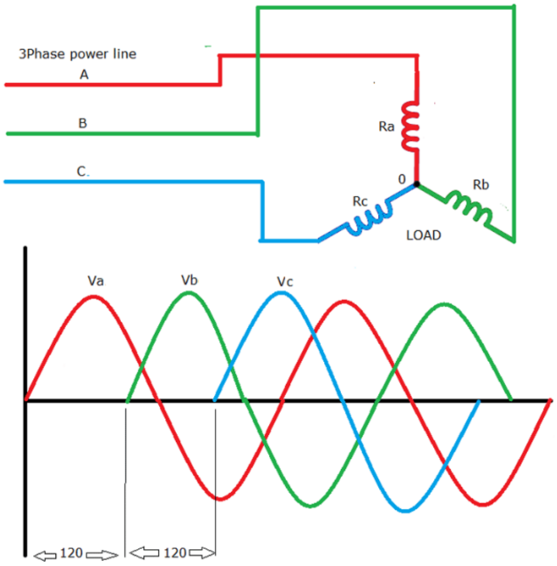


*Figure 6: **Example 3 phase output showing offsets of 120°** [2]*

The VFD that will be used to drive this motor is the WEG Electric CFW100. This motor was selected due to its compact design and relatively low price. The VFD has an amperage rating of 1.6A for the output phases and the nominal drive output voltage is 230 VAC. Due to the motor remaining stationary throughout the testing, no battery source is needed, and the power can be drawn directly from a 120VAC outlet.

Results and Discussion

Computation and Data

Topic 1: Model Predictive Control

Model Predictive Control is built on the foundations of using mathematical algorithms on a model of a system to predict future behavior to be controlled. MPC can be compared to that of a chess game; as players think ahead and plan several moves ahead, so does MPC. MPC is constantly thinking about what moves it can make, what its opponent (gravity, wind, power limitations) may do in return, and planning what to do in response.

In the context of a transportation system like Hyperloop, MPC is utilized to control the speed and position of the pod. This means that the model of the system would include the dynamics of the pod and the track, and the constraints could include limits on the acceleration and speed of the pod to ensure passenger comfort and safety [3].

The MPC formulation works with a few distinct steps. At each time step, a model of the system is used to predict the future behavior of the system, then an optimal control problem is solved over a finite horizon to find the optimal control action that minimizes a cost function. The first control input of the optimal sequence is then applied to the system and as time advances one step, the procedure is repeated.

Although the specific formulation of MPC can vary depending on the application, there is a general form, as follows:

$$U{:}J = \sum [x(t+j|t) - x_{ref}(t+j|t)]^2 + \lambda u(t+j|t)^2$$

Subject to:

$$x(t+j+1|t) = Ax(t+j|t) + Bu(t+j|t), for\ j = 0, \dots, N-1$$

Where x(t+j|t) is the predicted system state at the time t+j given the information available at time t, u(t+j|t) is the control input at time t+j given the information available at time t. $x_{ref}(t+j|t)$ is the reference state, while A and B are system matrices. λ is a weighting factor, U is the sequence of control inputs and N is the prediction horizon [4].

This is a very simplified version of MPC and it is important to mention that the actual implementation would be much more complex and likely involve nonlinear models, stochastic disturbances, multi-objective optimization and other advanced concepts.

Topic 2: Proportional Integral Derivative Control

Proportional Integral Derivative (PID) Control provides a more mathematical approach to control and correction. PID controllers provide a simple and straightforward approach as they do not require a model of the system in order to predict and make decisions on the future behavior of the system [4].

The PID controller calculates an error value as the difference between a measured process variable and a desired setpoint. The controller then attempts to minimize the error by adjusting the control inputs. In the context of a Hyperloop system, PID would be well suited in various areas such as propulsion, braking and levitation systems to ensure stability and performance. For example, a PID controller could be used to maintain the gap between the pod and the track by adjusting things such as magnetic field strength. The error in this case would be the difference between the desired and measured gap [5].

A PID controller can be mathematically represented by the following:

$$u(t) = Kp * e(t) + Ki * \int e(t)dt + Kd * \frac{de(t)}{dt}$$

Where u(t) is the controller output, e(t) is the result of the error = desired output – measured output and Kp, Ki, Kd are the proportional, integral and derivative gains, respectively. When applying the specific parameters of the PID controller to a Hyperloop system, it would depend on the specific design requirements of the system and would typically have a thorough system identification and tuning process.

Mechanical

Topic 1: Methods of Reducing Magnetic Field Strength

Two methods were found to reduce the strength of magnetic fields. The first is the application of an opposing magnetic field that is equal in magnitude [6]. This can be accomplished by using an electromagnet, with the team choosing to use a coil-based electromagnet powered using direct current. Further data on the magnitude of magnetic forces experienced by the Hyperloop pod must be collected before numeric calculations and empirical evidence can be collected. It is likely that this data will become available during the 2023-2024 academic year as the team completes its model LIM.

The second option is to use an electromagnetic shield. As discussed in Background Information, the effectiveness of shielding material is dependent on material properties of permeability saturation. As such, the ideal material should process high permeability and saturation.

Mu-Metal is a specialized material composed of 80% nickel, 5% molybdenum, 0.3-0.5% manganese, 0.1-0.4% Silicone, and balance iron [7]. It possesses an extremely high permeability but suffers from a low saturation point. This can be resolved by increasing the thickness and surface area of the shield or layering it with other materials. However, it is also much more expensive and exotic than steel, which could make procurement difficult.

Table 1 and Table 2 contains material data for steel and Mu-Metal under AC at 0.4 A/m and DC conditions respectively.

Table 1: ***Permeability and saturation of steel and Mu-Metal under 0.4 A/m AC conditions***

Material	Steel	Mu-Metal
Relative Permeability	800-1500	75,000
Saturation Point	22,000 G (2.2 T)	7,500 G (0.75 T)

Table 2: ***Permeability and saturation of steel and Mu-Metal under DC conditions***

Material	Steel	Mu-Metal
Relative Permeability	1000-3000	400,000
Saturation Point	22,000 G (2.2 T)	7,500 G (0.75 T)

The drop-off in permeability under AC conditions is due to the skin effect [8]. Electromagnetic fields induced by AC currents will not penetrate through a material but rather travel around the material near the surface layer only a few mm deep. For every skin depth, attenuation drops by 8.7 decibels. As such, a thicker material makes for a better shield, but only to a certain degree. In an AC field, multiple layers of shielding material separated by an air gap is more effective than a single, thick layer [9]. Skin depth is formulated as

$$\delta_S = \sqrt{(\pi \cdot f \cdot \mu_0 \cdot \mu_R \cdot \sigma)^{-1}}$$

f is the frequency in Hz, μ_0 is the permeability of free space, μ_r is the relative permeability of the conductor material, and σ is its conductivity in mho/meter. Since skin depth is a function of frequency, the shielding effectiveness of a material is inversely proportional to frequency. Figure 7 shows the change in skin depth, and in turn, permeability, of titanium, aluminum, copper, and mild steel at various frequencies.

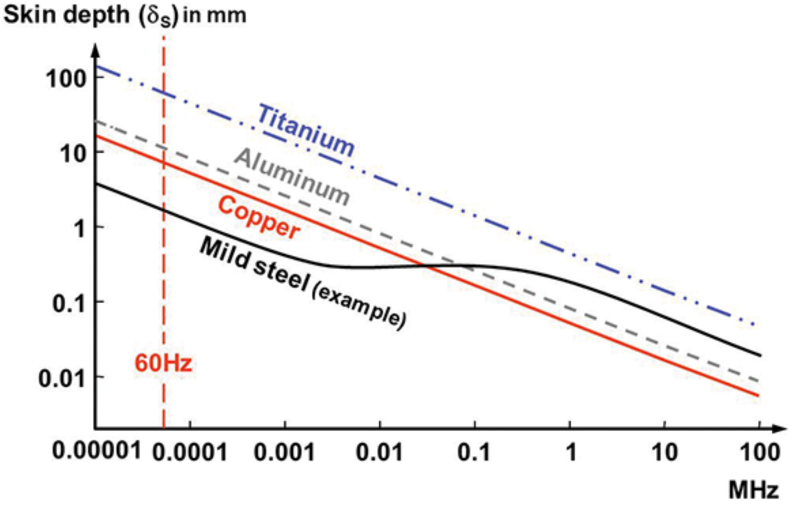


Figure 7: ***Skin depth of various metals at a range of 0.00001 to 100 MHz*** *[10]*

It can be observed that while most elements behaved linearly, mild steel experiences a relative increase in skin depth compared to other materials at higher frequencies. This results in a drop of relative permeability; as such, at frequencies greater than 0.2 MHz, steel is no longer the best choice for magnetic shielding.

Topic 2: Methods of Eliminating Induced Currents

Induced currents occur when a conductive material experiences a change in magnetic flux. As the linear induction motor operates using oscillating magnetic fields, the magnetic flux will also oscillate and induce currents. Therefore, the problem of eliminating induced currents reduces to a problem of controlling magnetic fields, similar to what was studied in Topic 1. The notable difference however is that there is no concern over the strength of the magnetic field, only how fast it changes. The Bio-Medical Division at the University of California created a prototype of an apparatus designed to cancel a magnetic field at any point during its oscillation. Their design assumes a magnetic field with sinusoidal oscillation with a frequency of 60 hertz. Although this yields a more simplified apparatus than what would be required for QHDT, it provides proof of concept for future experiments. The scientist's design utilizes the fact that any magnetic field in 3-dimensional space can be broken down into three mutually perpendicular components. Three magnetic fields that are equal and opposite to the three mutually perpendicular components of the oscillating magnetic field, cancel out the oscillating magnetic field. To accomplish this, three mutually perpendicular power coils are arranged and powered using AC current operating at the same frequency of the oscillating magnetic field, 60 hertz. A 6-way tap switch with five decks is wired to each power coil such that three of the five decks adjust the phase of the voltage by 60°, and the remaining 2 decks adjust the polarity. Two Variac variable transformers are used; one to continuously adjust the voltage within its 60° phase adjustment, and a second one to adjust the amplitude of the voltage. A schematic created by the Bio-Medical Division is shown below [11].

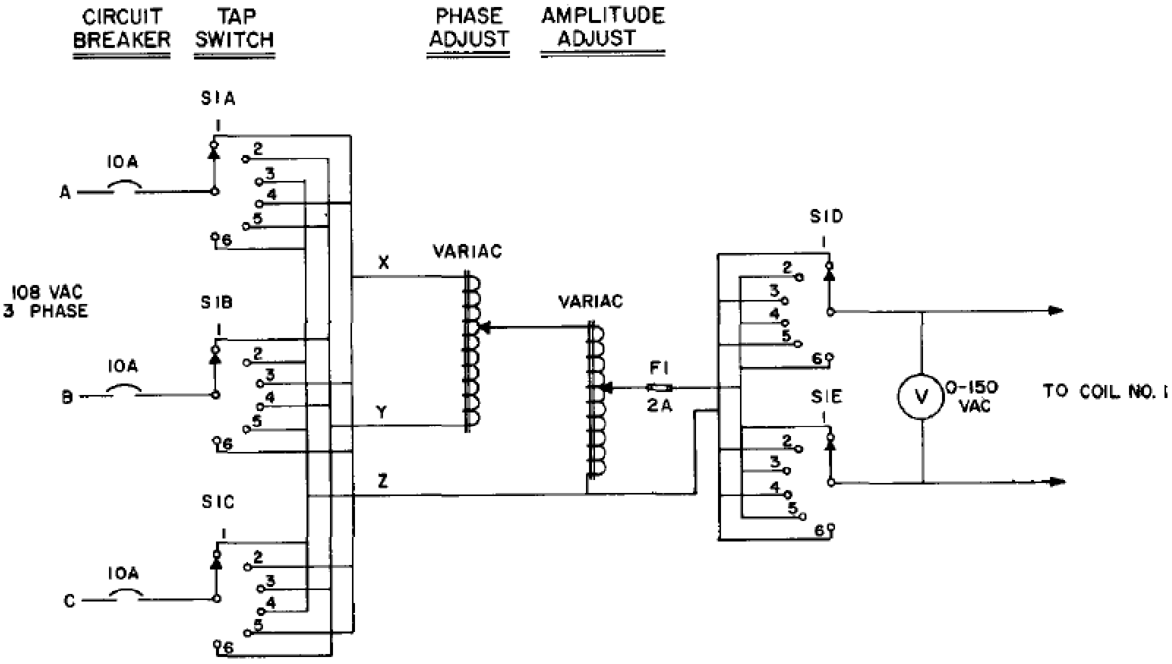


Figure 8: ***Schematic of magnetic field cancellation device***

Electrical

The process of assembly and testing of the LIM is still ongoing, so while the team does not have access to quantitative results, several existing qualitative results can be used in the development of current and future QHDT projects. The biggest area of improvement thus far is in the VFD. The VFD selected for this project lacked sufficient power and complexity. A larger amount of output, current, and voltage is needed for a motor of the size that is being tested. The VFD must also include integrated control systems, allowing for the controller to sweep through a range of frequencies and adjust as needed for thrust. There are 2 options for the VFD moving forwards: purchasing a more sophisticated VFD or designing and manufacturing a custom VFD. Purchasing a VFD is the more realistic option for the immediate future of the team, but as the LIM is integrated into a full-size pod, the team may need to design or adapt a VFD as needed.

Another item the team can improve on is to have the coils for the LIM custom made. Having the coils professionally machined with a rectangular cross section can allow for increased current density due to the greater filling factor over stock magnet wire. Such improvements will allow for greater efficiency of the overall LIM design.

Future Work

Future research endeavors potentially encompass refining motor efficiency, minimizing energy and data loss, exploring cutting-edge materials, and developing novel control strategies. Additionally, the integration of the motor prototype into a complete Hyperloop system and subsequent full-scale tests will yield valuable real-world insights for its practical implementation. By advancing the efficiency, power-to-weight ratio, thrust force, and active control of the LIM, it holds promising prospects for integration within Hyperloop transportation systems.

Mechanical

With the knowledge from this year's research, future work will consist of gathering empirical data and comparing it with existing literature. This will offer a better understanding of the fundamentals of electromagnetic fields and the effectiveness of shielding. Testing methodology should consist of utilizing EMF sensors, a dynamic or static EMF generator, and shielding materials. One potential design of interest was published by online educator FesZ Electronics, as seen below:

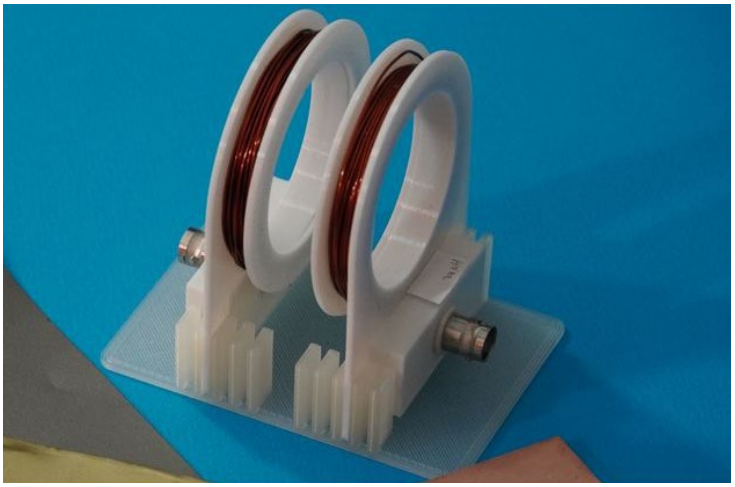


Figure 9: ***Plastic rig housing two inductors designed by FesZ Electronics***

The design consists of two inductors situated on a plastic frame with variable offset distances, with one inductor connected to a power amplifier and signal generator, and the other connected to an oscilloscope and a termination resistor. Thin sheets of shielding material could be placed in between the inductors. This design allows for precise adjustments to the induced signal, producing a wide range of frequencies as well as reliable data collection.

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