Design of Linear Induction Motor and Electrodynamic levitation for Hyperloop pod

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I. INTRODUCTION

Hyperloop IITB is an interdisciplinary engineering project wherein the objective is to build a prototype high-speed Hyperloop pod, that can travel at transonic speeds in a partially evacuated tube. Our original aim was to build the pod for the Hyperloop Pod Competition organized annually by SpaceX. 'Hyperloop' is a recently proposed means of transportation meant to compete with high-speed railways. The distinction in Hyperloop is the elimination/reduction of contact friction and viscous drag by using magnetic levitation and running the pod in a partial vacuum.

II. LINEAR INDUCTION MOTOR

Achieving incredibly fast ground speeds of over 1000 km/h or 600 mph yet being energy-efficient can only be realized by means of a magnetic linear accelerator. We believe that a Linear Induction Motor(LIM) is the right option for our system due to its ease of achieving high acceleration and decelerations, having almost no loss of energy due to friction and its high power efficiency. A linear induction motor, as the name suggests, is a linear motor working on the principle of electromagnetic induction similar to its rotational counterpart. A basic analysis of the system can be done by considering it as an unrolled version of the rotational induction motor, which has been studied extensively.

Since LIMs don't make use of any fossil fuels it does not release any harmful gases and hence eco-friendly. It is also a low maintenance transport system with zero emissions and can work with any excessive threat from weather or any natural calamity. LIMs are capable of producing good thrust and lift at high speeds. LIMs require very low energy as compared to any other transport system, the operational costs are also less. It can replace the conventional railways and high speed transport system present now. Environmental and power consumption considerations also point toward using LIMs in Hyperloop rather than BLDC driven pods on wheels, which cannot operate at the high speeds Hyperloop is slated to achieve.

III. LIM DESIGN

Currently the major LIM design used is a short primary design, where the primary is placed on the pod. For the secondary of the motor we have two choices:

- A two sided LIM, in which the secondary is the I beam which is shared by the two primary on either side.
- A one sided LIM, is a one in which the rotor will be the metallic sheet on the track.

A. Objectives:

- To achieve the speeds about 100m/s with reasonable thrust force to overcome the drag and other resistive forces.
- To identify the key parameters which determine the effectiveness and efficiency of an LIM system by parameter sweeping.
- To ensure smooth transition from BLDC drive to LIM drive at the critical speed of about 10 m/s when the magnetic levitation kicks in and LIM can propel itself with acceptable efficiency.

B. Key design decisions:

In the design of the primary we have 24 slots and single layer winding of three phase current. In the stator we have double layer winding of wires of 3 phase current. The design is based on the model found on "Linear Induction Motor (LIM) for Hyperloop Pod Prototypes"

The first key decision is to use a single sided LIM. This decision is based on current track specifications. The need to use two LIMs working on either side (using the aluminium plates) rather than 1 LIM using the I-beam rises naturally when the weight of the pod is considered in relation to the width of the I-beam. While the braking and suspension systems can use the I-beam it is impractical to use for the primary propulsion system of a pod being designed to run for 10 miles (as mentioned by Elon Musk on Twitter)

The next decision is the mounting of the LIM to the chassis of the pod (short primary design). Special provisions have to be incorporated into the design of LIM and the chassis contact region to accommodate the wiring of LIM and to ensure uninterrupted working of the machine.

Frequency has to be increased in order to have a shorter LIM, High Voltage used to reduce Joule heating and increase efficiency as sophisticated active flow based cooling mechanisms must be incorporated, due to lack of air-cooling that is generally available in any typical design, due to the soft vacuum operating condition. (pressure is less than 1000 Pa)

C. Methodology:

Simulation in COMSOL Multiphysics to simulate the electromagnetic forces in the LIM. Parameter sweeping in both mechanical (geometry, velocity) as well as electrical (frequency, current) parameters to the dependence of Thrust produced by LIM on them. Current design is being iterated to get 100 N of force at 150 m/s (the design maximum) to counteract magnetic and the very little aerodynamic drag.

D. Expected outcome:

Expected to produce a design that improves performance at every iteration. To optimize the design to reach cruising speed as soon as possible and at the expense of least amount of energy.

E. Future scope:

Our aim is to manufacture the optimal design, and test it to check the validity of our calculations, assumptions and key decisions made throughout the process. To further increase the speed to 200 m/s maintaining efficiency is the first task to increase the effectiveness of the system to replace conventional transport modes by a considerable margin by multi-fold reduction travel times and safety. We hope to replace short haul flight travel with Hyperloop to reduce the environmental impact of such frequent short-haul flights and cut down on travel duration significantly.

IV. LEVITATION SYSTEM DESIGN

The success of the implementation of LIM depends heavily on the levitation system design. The track design of Hyperloop competition as held by consists of aluminium plates on either side of the I-beam. Since there are solid plates of aluminium with no coils running around them, the only possible way of achieving levitation is by using eddy currents. Eddy currents are loops of electrical current induced within conductors by a changing magnetic field in the conductor according to Faraday's law of induction. By Lenz' law, eddy currents always oppose the changing magnetic field. Hence, magnetic levitation is always passive in nature, i.e. it always opposes motion. We need time-varying magnetic fields to produce eddy currents in the sub-track. These can be achieved in 2 ways:

1. Using electromagnets with time-varying currents
2. With relative motion between a permanent magnet and the sub-track

The advantages of using permanent magnets are:

1. No power source needed to operate.
2. High power density compared to electromagnets of the same size
3. No power-electronics needed to operate

The disadvantages are:

1. Expensive
2. No control over activation or deactivation of field

Much higher magnetic flux densities can be produced using the same magnets by arranging them in a precise orientation known as the Halbach array. The Halbach array has many advantages:

1. It is self-shielding; i.e. magnetic fields are forced to only one side of the array while the other side is almost field free.
2. The magnetic flux follows a sinusoidal distribution along the length of the array. This means a smoother rate of change of field lines.
3. The overall flux density increases compared to using a normal N-S-N-S configuration.

Two magnets would be stuck side by side to make a single cube magnet, and an array of this cube magnet would become our Halbach array. These properties are used to develop a model in Ansys Maxwell, and a parametric sweep was performed with air-gap and velocity as the sweep parameters. The resultant lift force and drag force were calculated. The lift and drag plots of the levitation system is shown below, this system is being optimized for maximizing the lift to drag ratio and minimising the costs so that it gives a significant lift even for small velocities.

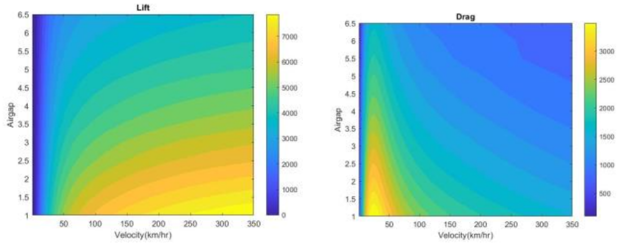

Figure 1. Lift and drag profile of Halbach array

V. SUSPENSION DESIGN

The pod requires a suspension system for two primary reasons one is to improve the dynamics while cruising, braking, and the other is to allow ride height adjustability. SpaceX intended to judge team-based upon their pod's vibration profile throughout the run hence improving the dynamics of the pod is essential. The magnetic field produced by levitation magnet has high stiffness and low damping, which results in under-damped oscillations in the pod and skis if no damping is introduced in the system. This is prevented by isolating the pod from the skis by the suspension. The free body in space has 6 degrees of freedom(DOF). It is necessary to maintain stability about all these degrees of freedom. Each DOF of the pod is controlled by the mechanisms, represented in table format. The mechanisms are based on more than one principle. The pros and cons of each are explained subsequently.

Rotation control about X-Axis(Roll) and Y-Axis(Pitch): To support the Halbach array, we need an extended component which is Lift skis. By controlling the magnetic field, we can control the roll and pitch of the pod, but this magnetic field depends on speed. A low-speed lift force is not sufficient to levitate the pod; hence there will be contact between pod skis and track which causes friction. Finally, it is better to combine the assembly of both so that a low-speed pod is supported by wheels and at high-speed when lift force is sufficient to levitate the pod.

Rotation control about Z-Axis (Yaw): Rotation about Z-Axis can be controlled by the lateral control module(LCM)

X-Axis translation control: We want the pod to cruise along the longitudinal direction; hence X-Axis translation is the only DOF which is not constrained except during braking. One of the measuring parameters of this competition is to minimize travel time for this pod. It needs to be accelerated to high speed and effective braking to stop the pod in minimum time.

Y-axis translation(Sway) control: It is controlled by Lateral control modules(LCMs) as their primary function is to keep the pod at the center of the track. The same LCM used for control rotation about the Z-axis is used to prevent sway of the pod.

Z-Axis translation(Heave) control: Levitation provided by

Halbach array has high stiffness and low damping resulting in an underdamped system. Such an underdamped system is prone to more vibrations. According to SpaceX specifications for the track, a "step" of 1mm might be present due to the placement tolerance of the aluminum plate sections. Such a step while cruise will cause step or impulse force disturbance to lift skies results in pod oscillations in pitch and heave. Passive suspension once designed then stiffness and damping remains constant this not in case of active suspension, here we can control stiffness or damping. Passive suspension can absorb and store energy while active suspension can also provide energy to the system. This is useful while taking turns, accelerating and decelerating to avoid pitch and roll. However, the active suspension is relatively challenging to design and implement and also expensive. Active systems may even be used to achieve better control over contradictory requirements. An example of this is the longitudinal stiffness of the suspension which should be low while taking a turn over curve track and should be high to maintain stability on straight tracks, especially during acceleration and deceleration. Meeting such contradictory performance requirements by passive suspension is difficult while the active suspension can solve this type of contradictions.

Disturbances coming due to placement tolerance of the aluminum plate sections of tracks are an order of 1mm, and the effect of such disturbances will be minimized by suitable design of the passive suspension. To be on the safer side, for the first iteration of suspension design, it is better to go with passive suspension.

From the figure below showing the lift and drag profile be seen that there is a negligible drag force due to this module at the same time providing a high lift to drag ratio which makes it an ideal system to be used as LCM.

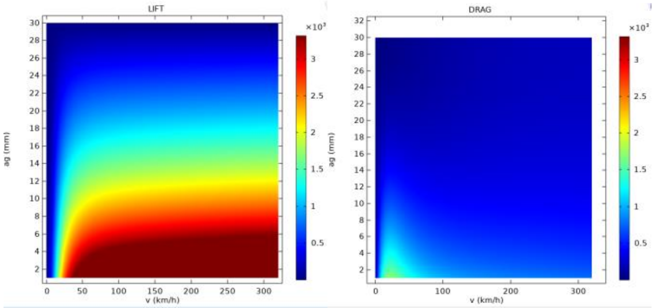

Figure 2. Lift and drag profile of LCM module

Design of Passive suspension:

For the design of passive suspension first, we consider the quarter pod model. For this model, we need to determine the spring stiffness and damping coefficient of the damper. For this disturbance stiffness(K) and damping coefficient(C) of suspension are selected such that the system will have the maximum acceleration of 0.1G in the z-direction and settling time for 2% ripple is 5 sec. This problem was solved in MATLAB SIMULINK for different combinations of K and C. After performing iterations; we found that values of K and C are 10000 N/m and 800 N-s/m for which system gives a maximum acceleration of 0.72m/s^2 which is less than 0.1G and also settles within 1.5 sec. Above response of suspension is obtained for only one step. As this step is due to tolerance at the joint between Aluminum plates of the track and each plate length is 12.5 feet so, in the worst condition disturbance may occur at each joint. If we take the speed of the pod as 200 kmph, then the time between each such disturbance is 0.06858 sec. For the same values of K and C, the maximum acceleration is 0.35 m/s^2, which is less than 0.1G.

Assembly of Suspension: If we assemble a spring-damper system between the pod and lift skis vertically, then, suspension system will bend due to lateral and longitudinal loads. This can be avoided by using the four-link mechanism, having one link in the form of suspension. One of the designs of the mechanism is as shown in the figure below. Similar mechanism with some modification can be used.

VI. ELECTRICALS AND CONTROLS

The pod requires a consistent and safe source of voltage across actuator systems, sensors and onboard computation. Design priorities include but not limited to safety, reliability and workability.

A. Battery and BMS

The tractive system for the BLDC and the linear induction motor(LIM) has been chosen with a maximum voltage of 712VDC, supplied through Lithium Ferro-Phosphate pouch cells, arranged in stacks of 13 cells and 15 stacks are to be used. Cells are to be joined using pressure fitting for ease of maintenance. Cells will be mounted on FR (or equivalent rated) ABS mounts with PCM pouches used for cooling purposes.

Battery management systems will be made in house and shall follow a slave-master communication protocol and use LTC-6804 (or similar) on slave PCBs. Error signals would be generated according to temperature or voltage measurements which would trigger shut down of the entire tractive system and safe discharge of the motor controller. Safety measures such as response times, shutdown circuit shall be compliant to Formula Student 2020 rules as they've been well tested and sufficient safety standard. During discharge, cells shall be passively balanced, and during charging, active balancing shall be used.

B. Accumulator Control System

This subtopic refers to safe and optimized channeling of high voltage and supplying low voltage systems with adequate noise-free power.

A 12V supply will be available for all control systems and shall be chassis grounded. An IMD (Insulation Monitoring Device) shall indicate through an error signal if HV and LV ground get connected (in no error state, they're expected to be isolated) Following is a block diagram for the BLDC circuit. LIM circuit is yet to be finalized due to difficulty in finding high power components suited for mobile applications and thus shall be incorporated later. Initially (when the motor controller is fully discharged), precharge of the motor controller shall be done to 90% of accumulator voltage, and then MC will be shorted to the battery. After the pod reaches a set velocity, a switching mechanism shall switch battery power to the LIM inverter as BLDC will not be needed.

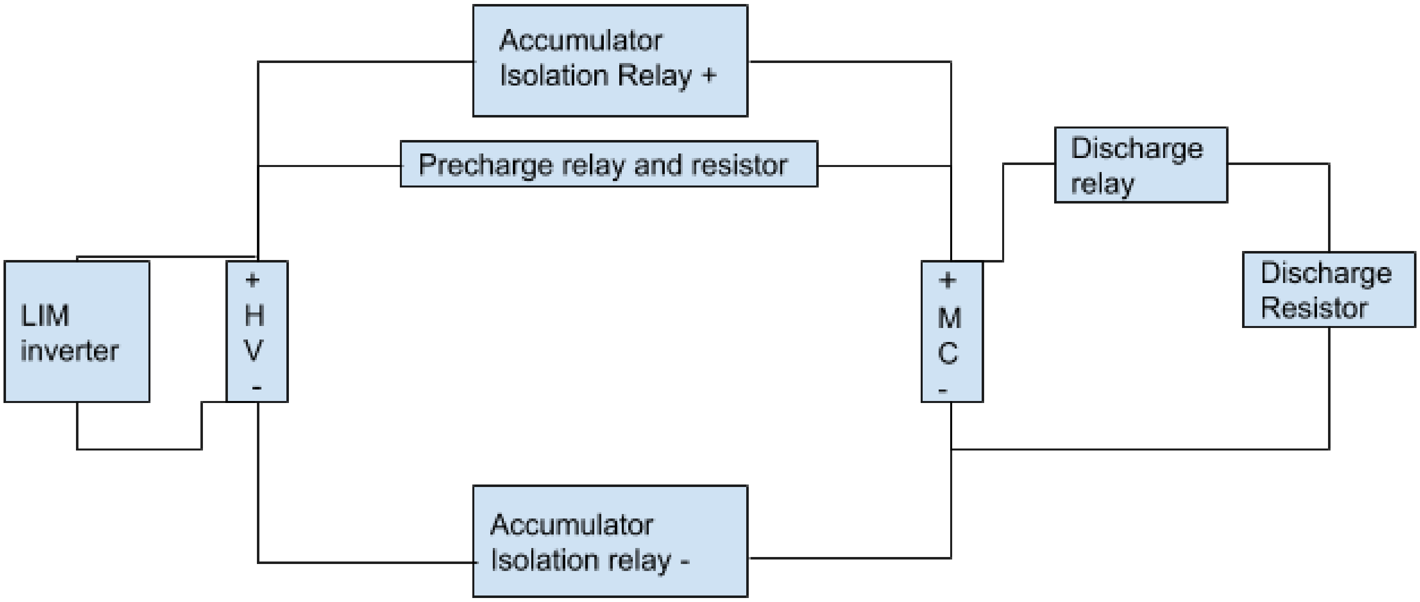

Figure 3. Schematic diagram of the HV circuitry in the pod

C. Shutdown system:

A voltage level (12V) shall be maintained as a safety indicator, and any signal resulting in the voltage drop shall result in the pod going into error mode. Error mode will completely isolate high voltage to the Accumulator Container and safely discharge the motor controller and LIMs.

Events triggering shutdown:

- BMS error due to high temperature, voltage falling below a set value, disconnection of a stack.
- The error signal generated by the motor controller due to overheating, etc
- IMD error: HV and LV ground shorted
- Disconnection or loose connection of motor controller/HV wires
- Improper switching of Precharge relay
- Improper switching to LIM inverter
- Signals which are given externally due to controls error/user-triggered shutdown

Also, an HV disconnect will be installed (which directly breaks HV+ path) for use in case of an emergency. Master switches shall control whether HV and LV are active at a given point or not. A data logger outside of accumulator container shall collect current and voltage of the HV system and send it to the CAN bus to keep data for future reference.

D. Accumulator Cooling

PCM (Phase Change Material) pouches (made for 50℃) will be used to keep the cells under 55℃ temperature specified by the manufacturer. An active cooling system is under consideration. Since pod runtime is not estimated to be long enough to cause thermal runaway considering only PCM usage, an active cooling system remains a theoretical pursuit due to disadvantages over PCM such as increased weight and system complexity.

E. Controls system:

Controls and communication systems are extremely essential in terms of reliability and workability and thus need to be optimized. Current tentative designs include using two Raspberry Pis for on board computing and controls (two for safety purposes and more speed and less load per device). An array of sensors including but not limited to: non contact temperature sensors inverters(contact for accumulator, PTC resistors), Hall effect current sensors for HV and LV current monitoring, voltage sensors for accumulator (as a part of BMS), brake sensors, accelerometers, gyroscope and control output from inverters and motor controllers.

The above data, processed in real time decides pod state and triggers shutdown when unsafe state is reached. Meanwhile, sensor data is transferred to user in real time using wireless communication protocols such as XBee. Actual delay times remain subject to experimentation, working conditions etc but design expectations and safety parameters indicate a safety-centric controls system.

VII. CONCLUSION

A Hyperloop pod is a huge, intricate and interconnected system that often takes years to conceptualize, test and build. We are a student team that attempt to do this. So far, we have managed a large section of mechanicals and decided on a propulsion system overview (which we like to call as a phase 1). A phase 2, which is more on the nitty gritty of the pod's electrical and propulsion systems (especially with a system like this) is underway currently. Phase 3 shall include all of electrical testing and control system setups. We really hope to assist in the Hyperloop project efforts, in whatever way possible and give a safe, well-functioning and tested pod from IIT Bombay.

VIII. REFERENCES

1. Musk, Elon, 2013, Hyperloop Alpha.
2. Timperio, Christopher, 2018, Linear Induction Motor (LIM) for Hyperloop Pod Prototypes