Development of Ryerson's Hyperloop Pod systems using a modular approach

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Abstract Current modes of transportation tend to be slow or expensive or a combination thereof. The Hyperloop is the next mode of transportation that aims to shift this notion by being fast, and inexpensive after being commercialized. In order to drive a revolutionary change within the transportation industry to better interconnect cities, our work focused on the development of various Hyperloop Pod systems using an innovative, and a modular approach. Modularity and standardization allowed for the rapid development of Hyperloop systems including MagLev and MagDrive systems for propulsion, mechanical and pneumatic systems for braking, and health monitoring and control systems for guidance, navigation and control.

Keywords Hyperloop · SpaceX · Pod · SRAD · Modular · Systems · Propulsion · Braking · Control

1 Introduction

Ever since the release of the Hyperloop Alpha document, great strides have been undertaken within the Hyperloop sphere. [1] This has been made possible by the research and developmental efforts being carried out by universities, and the industry. Current high speed travel is greatly impeded by air resistance. With aerodynamic drag increasing with the square of speed, a significantly large power input is required to go faster. This can be seen as power requirements need to be met with the cube of speed. By placing the Pod in a low pressure environment, this aerodynamic drag can be greatly reduced. This coupled with the implementation of contactless propulsion systems will aid in high speed travel that would otherwise have resulted in contact friction.

2 Hyperloop Tube

As the Hyperloop concept utilizes a low pressure environment, the system is proposed to be closed loop. The drawing of a hard to near hard vacuum has been avoided due to the difficulties that would be faced in order to maintain them. In addition, operating a low pressure environment would allow for the implementation of Commercial Off-The-Shelf (COTS) pumping systems.

The development of Ryerson's Hyperloop Pod has been based on the track built by SpaceX. SpaceX took it upon itself to build a Hyperloop Tube in order to accelerate the development of Hyperloop while providing university design teams the much needed resources to test, and validate their designs.

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The Hyperloop Tube at SpaceX is approximately a mile long steel tube fitted with two airlocks on either end. An internal guide rail spanning the entire length of the tube is placed within it, and is meant to be utilized by the Pods. As the operating environment is a low pressure environment, vacuum pumps have been fitted at regular intervals to maintain the tube within a predefined pressure range. With a pump down time of approximately 45 mins to 1 hour, the temperature within the tube is based on the time of day, and the weather as it is located outside with no built-in thermal cooling methods.

3 Testing and Validation Challenges

With the SpaceX's tube being located at their HQ in Hawthorne, California, an early issue that needed to be addressed had to do with the testing, and validation of the systems. The Pod being designed along with all systems needed to operate within a low pressure environment, using the track specifications as dictated by SpaceX at a varying temperature range.

As a university team, the possibility of travelling to Hawthorne more than once in a year was out of question mainly due to logistical and economic difficulties. To overcome this, a possibility that was looked into was to design and build an exact replica of the guide rail used by SpaceX. In doing so, testing could be conducted without the need to make multiple trips to SpaceX. In addition, it would open up the doors to an iterative design process where even minor modifications in the design can be tested, and validated relatively quickly.

Being a downtown university, square footage is a sought after, and an expensive commodity. As a result, the possibility of acquiring the required square footage to lay down a track along with its accompanying safety measures was next to impossible. Therefore, alternative methods for testing and validating the systems were looked into.

4 The Modular Test Rig

For development of the Hyperloop Pod, the entire vehicle can be categorized into three main systems: Propulsion (PRP), Structures (STR), and Guidance, Navigation and Control (GNC) with a few of their roles being listed in Table 1.

Table 1 Hyperloop Pod systems breakdown and developmental responsibilities

System	Development Responsibilities
Guidance, Navigation, and Control (GNC)	Health Monitoring System, Control, Telemetry, Pod Keep Alive Command
Propulsion (PRP)	MagLev, MagDrive, Power Systems
Structures (STR)	Chassis, Braking, Thermal Management, Vehicle Dynamics

In order to overcome the aforementioned space limitations, an innovative approach was taken where a modular test rig capable of accommodating tests from PRP, STR, and GNC was designed. The development of such a rig as shown in Figure 1 allowed for the validation of said systems individually, and while being integrated in conjunction with each other.

Figure 1 The modular test rig

Furthermore, the need to lay down a guide rail was completely eliminated by making the test rig to rotate. By doing so, an infinite track was created while occupying very little square footage. Through this approach, a total of approximately 15 ft^2 was used rather than approximately 450 ft^2 that would have been needed to lay down around 150 ft of the test track. The test rig itself can be broken down into: Support Frame, System Mounting Frame, Track, and the Motor.

Table 2 Breakdown of the modular test rig and material selection

Component	Purpose	Material Selection
Support Frame	Allows for the modular test rig to be bolted to the ground	High Strength Steel
System Mounting Frame	Allows for the integration of the track to the rig while providing a modular method of testing various systems	Aluminum (Al 6105-T5)
Track	Allows for characterization of system behaviors such as PRP, STR, and GNC	Replication of the guide rail at SpaceX
Motor	Provides a means to rotate the track at a specified RPM	N/A

The manufacturing of the track using the same material as that of SpaceX's allowed for the characterization of the developed systems. It ensured similar behavior would be observed had they been conducted at SpaceX. This was critical to generate the much needed data for the MagLev, MagDrive, Eddie Current braking, and GNC systems as they were dependent on the material properties of the track being used. In addition, using a large enough diameter for the track on the test rig provided a sufficient testing area. The incorporation of standard Aluminum extrusions around track provided a method of support for the various systems that required testing all the while the pillow block bearings allowed for the track to rotate smoothly no matter the RPM the motor was set at.

4.1 System Testing

4.1.1 GNC

Although the Pod is completely autonomous, a constant stream of data flows between the Pod and the Ground Station (GS). As data is continuously transmitted some of the parameters monitored have been shown in Table 3.

Table 3 Sample parameters monitored by GNC

Parameter	Data Transmission
Pod Position, Velocity, and Acceleration	To GS
Pod Health	To GS
Pod Keep Alive Command	To Pod
Pod Manual Control	To GS / To Pod
Ambient Tube Temperatures and Pressures	To GS
Pod Component Specific Temperatures	To GS
Pod Ground Clearance Height	To GS
Pneumatic Air Tank and Piston Pressures	To GS
Brake Positions	To GS / To Pod

Although the GNC tests were performed in a pressurized environment, all electronics needed to be vacuum, and thermal certified. This included the use of space grade solder and solder paste, and x-ray imaging of all the joints to guarantee performance in a low pressure environment. [2]

With the Hyperloop tube having a reflective circumferential tape placed at regular intervals, the navigation mechanism consisted of a stripe counting sensor that provides the absolute position of the Pod. [3] The testing of the stripe counter on the test rig allowed for its fine tuning in order to compensate for reflectivity of the material as the laser needed to be reflected off it. Furthermore, the lighting setup present within the tube could be accounted for in order to generate accurate results. In addition to validating the method used to determine the location of the Pod, some of the Pod states shown in Table 4 could also be tested.

Table 4 GNC Pod Test, and Run states

State	Description
Fault	Automatically stops the Pod when any non-nominal, unknown or unsafe circumstances are observed.

Safe To Approach	Indicated that the Pod is stationary, in standby condition, and is safe to be approached by humans.
Ready To Launch	Test systems and prepare systems for launch.
Launch	Accelerate Pod to a predefined target speed.
Levitation	Deploy MagLev system upon reaching predefined target speed.
Braking	Bring the Pod to a safe halt.
Crawling	Move the Pod at a very low speed using manual control from GS.

4.1.2 Structures Testing

When designing the braking system, key considerations included the distance it takes to stop, braking effectiveness, reliability of the system, and the resulting temperature change of the track. As the Pod undergoes multiple state changes as outlined Table 4, the ability to deploy the brakes is present in all of them. As a result, multiple tests were needed to characterize them.

The Pod contains two independent pneumatic braking systems while each system has the ability to deploy two brake pistons simultaneously. To ensure the stability of the Pod during all braking phases, the braking systems were placed at the front and rear of the Pod. To validate this design, a simplification was made where only one of the systems was mounted on the test rig. This was done to obtain braking data for the worst case scenario, i.e. one system is inoperable. This setup can be observed in Figure 2 where the two pistons are mounted to the mounting frame on either side of the test track.

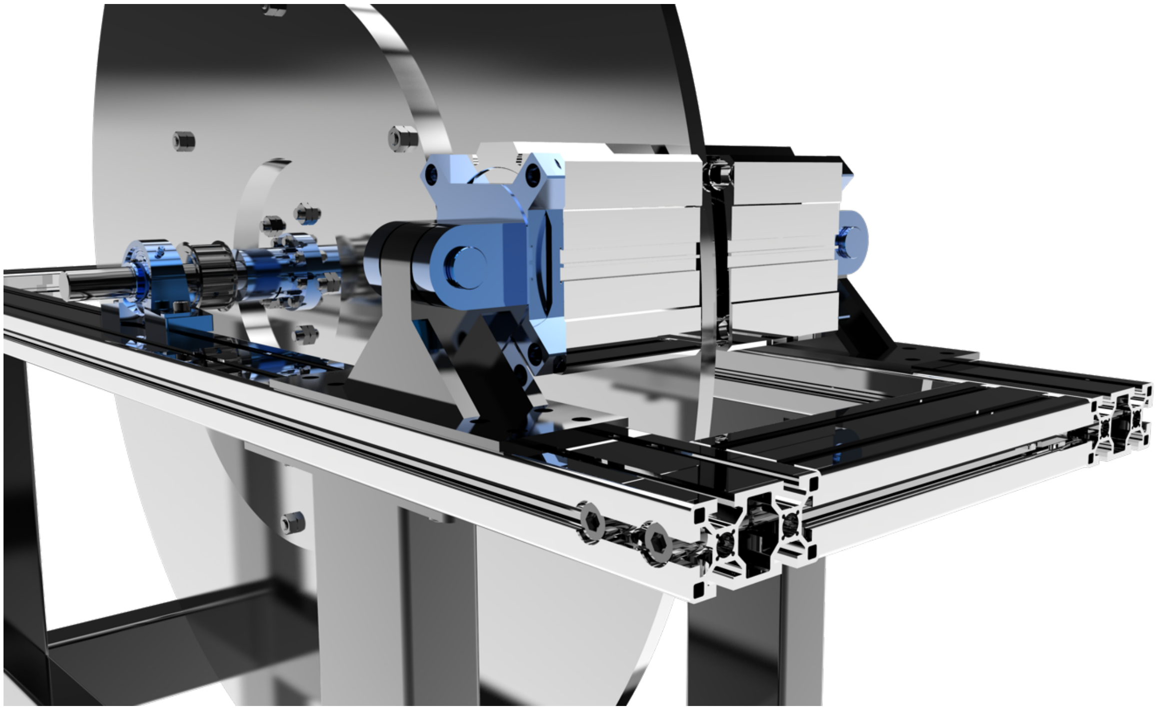

Figure 2 Test rig setup with brakes mounted on either side

Table 5 Worst case braking test parameters

Parameter	Value
Minimum Coefficient of Kinetic Friction	0.30
Maximum Velocity	60 m/s
Operational Systems	1 of 2
Operational Pistons	2 of 4
Scenario	Worst Case

For these tests, Table 5 outlined some of the parameters that were used. Data gather showed that this braking setup would be sufficient in bringing the Pod to a safe stop within the predefined braking distance. This was found to be sufficient in combination with one set being inoperable while still resulting in a Factor of Safety (FS) of two.

After the determination that the braking system was capable of bringing the Pod to a stop, its thermal characteristics were determined. Results showed that a temperature change of 11.895 °C would occur as a result of the heat dissipation between the brake pads and the track itself. Conduction was assumed to be the only source of heat dissipation as the operating environment would be a low pressure one. Furthermore, as convection and radiation accounts for a fraction of the value compared to conduction, they were ignored.

4.1.3 Propulsion Testing

In order to develop a propulsion system capable of propelling and levitating through a true contactless system, they had to be researched and developed from the ground up. MagLev, and MagDrive were the two main Student Researched And Developed (SRAD) systems of the propulsion system. [4]

MagLev is derived from the magnetic levitation system that is used to support the Pod along the normal direction at high speeds. [5] It uses a Halbach array to induce a repulsive magnetic field to suspend the Pod at a particular height above the track. Some of the main advantages of incorporating such a system were found to be:

- Contact or frictional drag was reduced when compared to wheels at high speeds
- A resulting improvement in the Pod's acceleration profile
- The design of a completely static system with no moving parts led to a much simpler design overall

With the MagLev system being SRAD, it needed to be validated thoroughly to show that a sufficient force or lift could be generated in order to levitate the Pod. To do so, a Dual Axis Force Transducer (DAFT) was developed to be tested on the modular test rig as shown in Figure 4. The DAFT was capable of measuring the lift and drag forces as a function of the test rig's velocity.

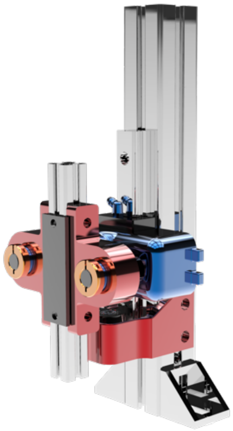

Figure 3 The Dual Axis Force Transducer (DAFT)

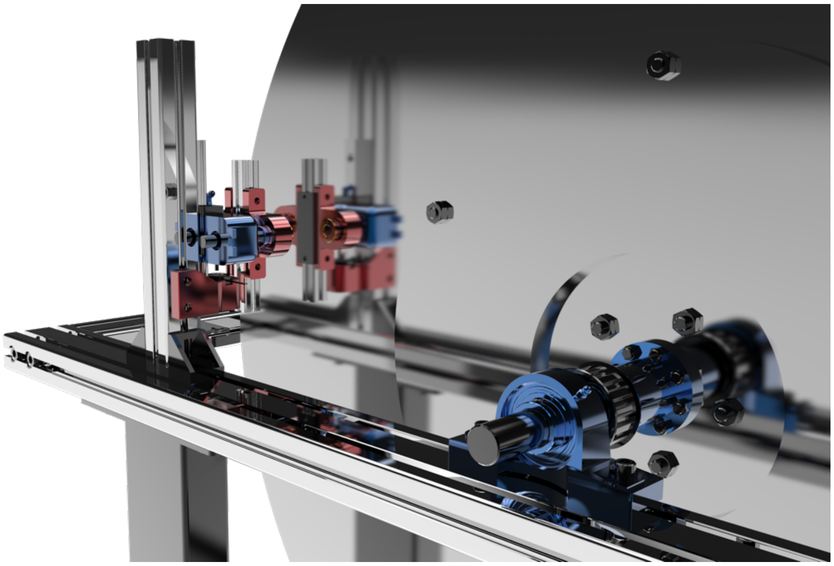

Figure 4 Test rig showcasing one of the two SRAD DAFTs mounted on it

Due to unforeseen issues, the test apparatus was only able to run up to a peak velocity of 8 m/s while holding the rotations at a constant speed reliably. Although this issue was encountered, tests were performed using the DAFT with a singular North-South period configuration of N42 magnets measuring 1” by 1” by 0.5”. In Figure 5, the readings taken between 0 and 4 clearly illustrate the ramp up in the test rig’s speed. Nearing peak velocity, the lift to drag ratio was observed to be 1, and can be seen in Figure 5 as well.

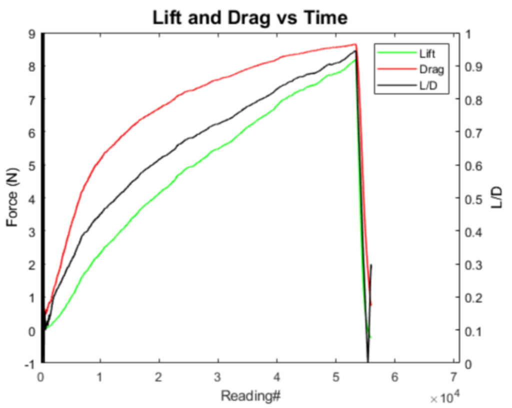

Figure 5 Testing Results of Lift and Drag vs readings

Using the results obtained from testing, a theoretical profile was generated to show the behavior had the speed been increased further. [6] Figure 6 also showcases the crossover point where drag begins to depreciate considerably as lift continues to increase. This occurs up a certain point after which both the parameters being to plateau. Using the observed trends, a relationship was developed along with it being used to calculate the lift at levitation speed. The relationship has been tabulated in Table 6. This estimate will be refined further based on tests resulting from the test rig going even faster.

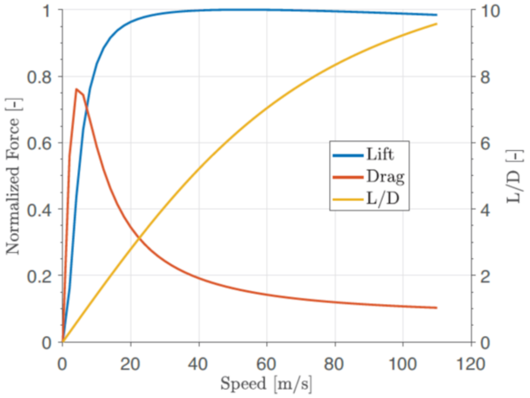

Figure 6 Simulation of Lift and Drag vs Speed

Table 6 Design parameter performance effect

Design Parameter	Effect on Lift	Effect of L/D	Effect on Weight
Array Wavelength	Slight Decrease	Square Root Increase	Increase
Number of Periods	Linear Increase	No Effect	Increase
Array Width	Linear Increase	No Effect	Increase
Array Thickness	Squared Increase	Negligible	Increase
Magnet Grade	Increase	No Effect	No Effect

Back Iron Thickness	Slight Increase	Negligible	Increase
Nominal Gap Height	Inverse Square Decrease	No Effect	No Effect

5 Conclusion

Having the modular test rig ensured that the SRAD systems could be validated with relative ease. Their characteristics and behaviors could be replicated without the need to utilize SpaceX's track during the various developmental phases. With the test rig not being in a low pressure environment, research still needs to be conducted on how the braking system would behave when operated in one. Further testing needs to be conducted using more magnet combinations after resolving the issues encountered during MagLev tests.

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