Numerical Investigation and Multi-Objective Optimisation of the Aerodynamics of a Hyperloop Pod

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Abstract
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1 Introduction

Rising environmental concerns have led people to shift from cars to public transportation systems. In order to account for the large influx of new users, existing mass transportation systems are required to be very efficient in ferrying a large number of people in less time. Current high-speed rail systems have a top speed of nearly 500 km/h but can only operate at much slower speeds (300 km/h). At high speeds, the contact friction between the rail and the wheels produces a lot of heat, thus limiting their performance. Moreover, since trains currently operate at ambient conditions, the form drag increases rapidly at high speeds. Maglev trains, which operate on the principle of magnetic levitation [**?**, **?**], are able to address this issue associated with friction heating, as they do not make contact with rails but are still limited by pressure drag at high speeds. These operational limitations of current vehicles motivated the research and development of hyperloop systems [**?**].

A hyperloop consists of pods that can be accelerated in partially evacuated tubes to over 1000 km/h. They are magnetically levitated on a central rail and are propelled using Linear Induction Motors (LIM). Inside the tube, the low-pressure environment ensures low air density, leading to lower form drag than vehicles travelling at similar speeds at ambient pressure. This, combined with an absence of contact friction, would enable operational speeds well beyond the capability of the existing railway systems. The hyperloop is planned to provide point to point connections at speeds resembling air travel. Maintaining efficiency at high operating speeds ($M_operational \quad 0.9$) requires robust aerodynamic design. While the pressure inside the tube is nearly 0.1% of the atmospheric pressure [**?**], it is necessary to carefully model the remaining air. Since transonic flow in confined tubes produce complex flow structures, it is difficult to simulate the phenomenon with high fidelity.

Due to low operating pressure inside the tube, the Re of the current flow lies in the transition region. This makes it susceptible to laminar to turbulent transition (insert citation). Since the flow can become locally supersonic over certain regions of the pod, they can also trigger boundary layer separations (insert citation). All of these factors contribute to an increased drag, in addition to the drag imparted by the choked flow [**?**]. The flow becomes choked at the point of minimum cross-sectional area between the pod and the tube and when it occurs, the mass flow rate cannot increase downstream, even if the pressure difference in the downstream is increased. There are two ways to ensure that the pod does not violate the kantrowitz limit. The first option is to decrease the blockage ratio, which is the ratio of cross sections of the pod and the tube ($B_r = \mathrm{A_{pod}}/\mathrm{A_{tube}}$). The other option is to introduce a compressor in front of the pod that can redirect excess mass flow rate to the back of the pod even when the B_r is high. While this option was initially proposed in the original introduction of the Hyperloop, it is difficult to simulate the aerodynamics of the pod in the presence of a compressor.

The objective of this study is to develop an aerodynamic shape optimisation framework for a hyperloop pod, taking into consideration the drag coefficient and the Kantrowitz limit. This is realised by performing 2 Dimensional (2D) numerical simulations using ANSYS Fluent, coupled with the ANSYS DesignXplorer optimisation interface. The optimisation routine controls the geometry using bezier control points and produces a geometry that minimises the drag force while staying within the Kantrowitz limit. The baseline pod geometry is designed in accordance with the minimum geometry requirements set by Hyperloop India, a student team at BITS Pilani, India.

This paper is structured as follows: Section 2 outlines the numerical methods employed in this work, followed by the problem definition in section 3. Section **??** provides initial results for the grid independence study. The optimisation framework is currently being developed, and the detailed results will be presented as part of the full paper.

2 Numerical Methodology

We carry out a Goal-Driven Optimisation (GDO) study based on the Multi-Objective Genetic Algorithm (MOGA) formulation. It is a hybrid variant of the Non-dominated Sorted Global Algorithm-II (NSGA-II) based on controlled elitism concepts. The constraint handling uses the same non-dominance principle as the objective functions, thus ensuring that the feasible solutions are always ranked higher than the infeasible ones. MOGA generates new population sets using cross-over and mutation. Cross-over combines two chromosomes (also called parents) to produce a new chromosome, such that it can be better than both the parents and take the best characteristics from both the parents. Two parent vectors are linearly combined to produce a new offspring. During mutation, one or more gene values in a chromosome are altered so that the algorithm is able to arrive at a better solution as compared to the previous iterations.

The spatial constraints in our problem is governed by the Kantrowitz limit, which is calculated using the following relation,

$$\frac{A_{pod}}{A_{tube}} = M_0\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \times \left(1+\frac{\gamma-1}{2}M_0{}^2\right)^{-\frac{\gamma+1}{2(\gamma-1)}} \tag{1}$$

3 Problem Definition

The objective of this study is to design a pod geometry that experiences the least drag force during its motion through the tube. The geometry is also governed by the Kantrowitz limit, which controls the maximum allowable pod height before the flow becomes choked for a particular pod velocity [**?**]. The baseline pod has a length L of 3.5 m and a height of 0.355 m. The flow domain is modelled according to a scaled-down version of the test tube at the SpaceX site and has a height of 1.4 m. The upstream and downstream lengths are taken as 5L and 10L, respectively, where L is the length of the pod. The blockage ratio $\mathrm{Br_i}$ is defined as the ratio of the projected area of the pod to the height of the computational domain. $\mathrm{Br_i}$ for this baseline geometry comes out to be equal to 0.253. In accordance with the Kantrowitz limit, the permissible pod velocity is Mach 0.5, for which the flow around the pod is exactly sonic. For our study, we have considered the pod velocity to be equal to 163.2 m/s, corresponding to Mach 0.476.

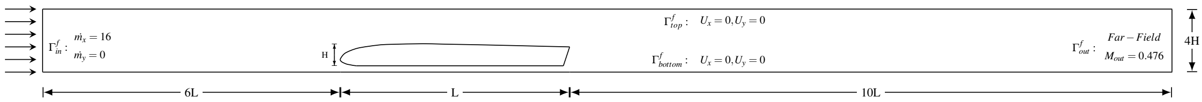

Figure 1: Solution Dike problems

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$$\begin{cases} w \geq 0 & \text{em} \quad R \\ 1-\Delta w \geq 0 & \text{em} \quad R \\ w(1-\Delta w) = 0 & \text{em} \quad R \end{cases} \qquad (2)$$

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Table 1: Numerical results

Iter	IterBL	ti	fn
0	0	0.000000	1.605e+001
1	0	1.000000	5.196e+000
:	:	:	:
:	:	:	:
31	19	0.730000	3.066e-009

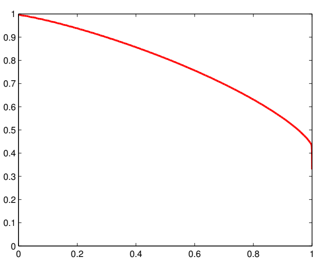

Figure 2: Solution Dike problems

3. Acknowledgements

4. References
References should be listed at the end of the paper and consecutively numbered. Refer to references in the text with reference number in brackets as [1]. Style the reference list according to the following examples.

[1] S. Missoum, P. Ramu and R.T. Haftka, A convex hull approach for the reliability-based design optimization of nonlinear transient dynamic problems, *Computer methods in applied mechanics and engineering*, 196 (29), 2895-2906, 2007.

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