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HYPERLOOP AS AN EVOLUTION OF MAGLEV

Hyperloop is often described as the "fifth mode of transportation" but, as the race between competing companies around the world intensifies, investors, governments and scientists remain cold and cautious. An educated guess from one of the first civil engineers involved with the design of a real-world hyperloop infrastructure tries to give some direction between hype and pragmatic design.

Keywords: Hyperloop, vacuum transportation, future transportation, tubes, civil engineering design, infrastructure

INTRODUCTION

In August 2013, Elon Musk (CEO of Tesla & SpaceX) and SpaceX released an Alpha study detailing a new form of transportation called the Hyperloop "*a fifth mode after planes*, *trains*, *cars and boats*". The Alpha study was intended to promote an alternative transportation system, after the California High Speed Rail proposed design.

Among various innovative design concepts, the study claimed that the Hyperloop could cover the 560 km distance between Los Angeles and San Francisco in an estimated time of 35 minutes, at an average speed of 970 km/h and a maximum of 1200 km/h, in contrast to the 2 hours and 38 minutes of the California High Speed Rail proposal, or the hour and 15 minutes of airplanes.

The Musk Hyperloop capsules are able to reach near Mach speeds by travelling through a low-pressure tube (approximately 100 Pa) and thereby minimizing the influence of drag and resistive forces.

That 2013 report marked the restart of the transportation technologies based on vehicles running inside an almost-vacuum environment. It was a restart because this concept has nothing revolutionary: More than one hundred years ago the Russian professor Boris Weinberg from Tomsk Institute of Technology developed the project of a train in which the cars would run inside an evacuated copper tube held up in the air by electromagnets and steering clear of its walls. Sources at Tomsk University explained that the project was hardly conceivable in the early 20th century and could not be put into practice because of the costs involved.

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From that time several concepts of vacuum transportation flourished around the world, having all similar main features.

Even Musk's white paper was often criticized to give oversimplified solutions to complex issues, it ignited new lifeblood to the stagnant and often lazy general concept of already established forms of transportation. While the industry and media had an overall positive and sometimes even enthusiastic response, the academic world reacted with cold and sometimes even conflicting opinions.

1.0. HYPERLOOP AS AN EVOLUTION OF MAGLEV

Magnetically levitated trains are undoubtedly the most advanced vehicles currently available to railway industries. Maglev is the first fundamental innovation in the field of railroad technology since the invention of the railroad. Maglev vehicles use noncontact magnetic levitation, guidance and propulsion systems and have no wheels, axles and transmission. Contrary to traditional high-speed railroad vehicles, there is no direct physical contact between maglev vehicle and its guideway. These vehicles move along magnetic fields that are established between the vehicle and its guideway. Conditions of no mechanical contact and no friction provided by such technology makes it feasible to reach higher speeds of travel attributed to such trains.

Even is not obviously the intent of this report to go into details about the Maglev technology, it is needed to define the two main suspension groups:

- Electromagnetic Suspension (EMS);
- Electrodynamic Suspension (EDS).

Both suspension systems show the same main features as safe travelling at high speed, low pollution because of electrically powered, low maintenance and high capacity to accommodate increasing traffic growth, but they are technically very different.

Performance of EMS system is based on attractive magnetic forces, while EDS system works with repulsive magnetic forces. In EDS system, the vehicle is levitated about 10 mm to 100 mm. above the track using Permanent Magnets (PM EDS) or Superconducting Magnets (SC EDS). In EMS system instead, the vehicle is levitated about 10 mm to 20 mm above the guideway using electromagnets.

The highest speed reached with a Maglev train is (at the present time) equal to 603 km/h and it was possible to achieve it using passive SC EDS technology adopted by the Japanese high speed L0 train series owned by JR Central (Central Japan Railway Company). The train uses the superconductivity phenomenon to obtain zero electrical resistance and thus a very powerful magnetic force. The magnets on board the vehicles achieve a superconducting state by cooling a niobium-

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titanium alloy with liquid helium to a temperature of – 269°C. The Propulsion, Levitation and Guidance systems are all installed in the sides of the guideway. Although the system is extensively tested and reliable, the costs of construction and operative are almost proibitive. Besides, due to the aerodynamic drag, its speed record might be not easy to outmatch.

Indutrack

The need to develop a simpler and cheaper Maglev led the USA to design the *Inductrack*, a technology that uses also passive EDS but with the adoption of Neodymium-Iron-Boron permanent magnets instead superconducting magnets.

In this design, an array of permanent magnets (Halbach Arrays) is located on the bottom of the vehicle that create a magnetic repelling field when they pass over passive coils on the rail bed. Each coil is a closed circuit, not connected to other coils or to an external power source. Thrust from linear motors propels the pods forward.

Hyperloop

All open air systems face a simple problem: aerodynamic drag. If we consider Maglev, it faces a lot of drag as speed increases. The drag forces quadruple as the velocity of the object doubles, and, to overcome that drag force it needs eight times the power to increase its speed. Thus drag limits the top speed for ground-based open air systems.

Hyperloop has been designed to overcome this. By operating in a low-pressure environment that allows for lower air density the system limits the amount of drag it would face to begin with. This coupled with a passive levitation system to eliminate friction and a compressor to channel the air in front of the capsule and funnel it to the back to generate extra thrust. The compressor is driven by an electric motor which gets its power from onboard rechargeable DC batteries.

In order to achieve very high speeds, the adoption of a linear induction motor (LIM) is the most efficient way to produce frictionless thrust able to overcome the aerodynamic drag.

Solar panels eventually cover the tubes structure to recharge the DC batteries. Standard commercial pumps could easily overcome the air leak and maintain the low pressure needed in the tube. The LIM is clean, and its maintenance is easy as it has no moving parts or gears.

While Hyperloop technology promises to be a highly innovative transportation mode that could enable true high-speed ground transportation, the development of the technology is still in early stages. The system is a large-scale engineering project, with development continuing on all elements of the vehicles and infrastructure, including propulsion systems, levitation systems, guidance and control, signaling, thermal and so on.

This technology is moving quickly, but will require coordination and acceptance from regulatory agencies on design, operations, security, and safety.

In the next sections of this paper it will discussed and briefly analyzed the main subsystems of the Hyperloop infrastructure.

2.0. TUBES STRUCTURES DESIGN

The Hyperloop superstructure is basically the tubes structure. It could be easily considered as a multi-span continuous bridge with the typical requirements that are prescribed for the high-speed railway system or even more stringent for the Maglev system.

2.1. SPACING ALIGNMENT AND CURVES

The vacuum tubes structure could be designed to be built overhead on pylons, at ground level, shallowly below ground, or deeply below ground, in accordance with existing terrain conditions and the requirements on the radius of curvature. Each method has its advantages and disadvantages. This paper will consider the elevated configuration of the vacuum tubes supported by piers. In this case the tubes structure is supported by a substructure at a regular distance and the loads are transferred to the pier with the adoption of structural bearings which constrain the tube in the vertical direction but allow longitudinal slip for thermal expansion as well as dampened lateral slip to reduce the risk posed by earthquakes.

Spacing

The spacing of the piers retaining the tubes is critical to achieve the design objective of the whole structure. In general, an optimal span length exists for elevated structures. Shorter spans reduce superstructures cost, but increase overall column, footing, and earthwork costs as more columns and footings are required for a given distance. In the infrastructure industry the average span is usually between 20 m to 40 m and, according to Musk's white paper *Hyperloop Alpha*, the spacing was considered equal to 30 m. The adoption of this span would make the static loads acting on the piers still quite reasonable due to the lightweight of the Hyperloop tubes and the vehicles, but the dynamic amplification loads could be very large due to the very high travel speed of the running vehicle.

Alignment

Most of the classical transportation systems on wheels have such gradients that do not cause relevant difference between the real 3D alignment and its projection on the horizontal plane. The Hyperloop system instead (as well as

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the Maglev) can go up to steep gradients (up to 10–15 %) and need then a very precise alignment stationing to be defined in 3D to provide exact location of the levitation equipment, precise evaluation of the centrifugal forces along to achieve comfortable and safe riding during accelerations/deceleration conditions. The use of height variation could sometimes be the only solution to achieve comfortable curves while keeping the desired design speed.

Curves

The curve radius has a strong influence during the alignment design because lateral g-forces above 0.5 g are usually considered not acceptable for comfort reasons.

The lateral acceleration of the curve increases with the square of the velocity and decreases with the turn radius, which results in a simple relationship between turn radius and vehicle velocity; as an example then, we can deduct that at maximum Hyperloop operative speed the tubes structure must bend at a minimum radius of 23.5 km to be comfortable for the passengers (Alpha document). It is then clear that this is one of the limitations to take in account during the design of the alignment because it gives limitations both on bending radius and the operative speed. Plausible alternative is to use a banking mechanism for the capsule as it goes around a turn. Yet, banking achieves less lateral acceleration at the expense of greater perceived vertical acceleration, which can give humans the sense of sea sickness. It may be possible to manipulate the height of the pylons to still reduce the resultant lateral accelerations while banking and transfer these to longitudinal, not vertical, accelerations that are tolerable.

The geometry where the Hyperloop structure can transition into curves from a tangent and the alignment geometry requirements could be generally comparable to the standard high-speed systems while the banking angles usually used to accommodate curve radii are not comparable since on Hyperloop system might be more limited. One of the most suitable transition curves that Hyperloop could benefit is the sinusoidal transition approach as it is described in the Eurocode norm for track Alignment EU 13803:1

The sinusoidal curve (also called “*Klein*”) provides smooth variation for the vertical and lateral jerk, without the sudden changes found for most of the transition curves, including the clothoid and linear. This smooth variation is an essential requirement in defining the alignment of the system. The design must not experience uncomfortable lateral or vertical g-forces and jerks through any curve.

2.2. DEFLECTIONS

An important guideway design issue for any elevated bridge-like infrastructure is the maximum deflection that can be allowed on each span. To ensure adequate ride quality, allowable beam vertical deflections due to beam dead weight as well as to all live loads are limited. Most commonly, static deflection criteria are presented as a ratio of the span length over a set numerical value, e.g. L/2200 for span greater than 10 meter is a vertical deflection limitation imposed by California High Speed Rail design criteria; Transrapid is set to L/4000. The deflection criteria must consider restrictions for both short and long-term behavior. Short-term deflection behavior is calculated according to elementary beam while long term deflections, due to material creep, shrinkage, and/or relaxation, are estimated as a percentage increase of short term beam deflection calculations.

When analyzing the vertical deflection limitations of the Hyperloop system, the roughness A, and its effect on passenger ride quality, the maximum dynamic vertical and horizontal deflections are perhaps more appropriate criteria measures since they are generally larger and more significative than static deflections. The dynamic deflections depend on several parameters among which are the natural frequencies of the tube structures, the vehicle dynamic properties, speed and even the vehicle throughput.

2.3. LOADS

Load effects typically refer to tube structure deflections resulting from static and dynamic forces and moments exerted on portions of the tubes structure. In addition, thermal expansion and contraction tendencies of the tubes can cause bowing and warping if allowances (e.g. sliding bearings) are not made for such movements. The acceptable tubes structure design must be capable of resisting all load effects within the constraints necessary for acceptable and safe system operation.

Dead weights

Dead loads are permanent gravitational loads on the structure due mainly to the density of the tube members. Other dead loads include the suspension magnet system, the track insert, the guidance magnet system, the cabling, insulation layers and so on. All those loads are usually considered uniformly distributed on the tube structure and are almost all located in the lower part of the tube

Normally, mostly of the dead loads result in an initial deflection of the beam. Depending on the construction material and technology of the tubes, we can also consider as permanent loads the pre-tension forces, the creeping and shrinkage. The dead loads of the auxiliary components of the tubes structures, they should be determined according to the relevant standards and regulations.

Vacuum

To reduce the drag force and manage shock waves as the capsule approaches the speed of sound, the Alpha paper suggest to set the operating tube pressure to

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100 Pa (1000 times less than sea level conditions). This negative pressure will act radially inside the tube walls and it must be kept constant.

Vehicle loads

Vehicle loads can range from uniformly distributed to concentrated point loads, depending on the loading pad configuration of the vehicle. Though any vehicle loading pad arrangement can be accommodated in the tube structural design, as size and strength requirements for the tubes are influenced by the distribution of the vehicle loading, the more distributed the load, the lower the tube structural strength requirements will be. Moreover, a more distributed loads will generally lower the dynamic effects.

Acceleration and Braking

The speed of the vehicle can be continuously regulated by varying the frequency of the alternating current of the propulsion system (e.g. LIM–Linear Induction Motor). If the direction of the traveling field is reversed, the motor becomes a generator which brakes the vehicle without any contact and the braking forces will act in the same trackside of the propulsion forces. It could also use a friction brake mechanism against the rails located on the interior tube wall for low-speed motion or emergency. Using as reference *the Maglev Construction and Operation Ordinance* (MbBO) the acceleration limits are set to 1.5 ms^{-2} for the drive, braking acceleration and lateral acceleration while for the normal acceleration is limited from –0.6 ms^{-2} to +1.2 ms^{-2} as comfort value.

Lateral force due to guidance

To make the vehicle laterally stable during the travel, there is a guidance system that will exert a force dependent with the velocity of the vehicle. This force should be considered during the design of the tube structures.

Centrifugal force

This force acts horizontally and with the direction perpendicular to the tangent to the horizontal axis of the guideway. It will cause moment around the longitudinal axis that will be transferred over the levitation magnets to the tubes structure. The tubes structure will load the bearings with axial tension and compression forces.

2.4. THERMAL

Thermal load effects are very significant in an Hyperloop structure. In case the support system is designed as constrained, changes in temperature induce additional thermal stresses on the tube structures. While instead the a simply supported scheme is chosen, the horizontal displacements must be accommodated by expansion joints with adequate displacement capacity. The bowing and warping

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of the tubes must be always avoided since they can develop uplift forces on the piers or/and excessive lateral and vertical deflections.

International codes often prescribe to increase of the environmental thermal loads by 1.25 for the design of the expansion joints and structural bearings. Hyperloop tubes structure should take in account at least the similar amplification factor.

Structural elements composed of materials having similar thermal expansion coefficients expand and contract uniformly, e.g. steel and concrete. In contrast, structural elements containing materials having significant differences in thermal expansion properties expand and contract non-uniformly. This non-uniform thermal behavior typically leads to internal thermal stresses, and potentially, to bowing of the element. The design of the tube structures should take in account this issue.

Thermal and blockage ratio

Some recent research studied the thermal-pressure coupling effect on blockage ratio in the almost-vacuum tubes structure. The results showed that when the speed of the vehicle and system pressure are held constant, the aerodynamic heating increases exponentially as the blockage ratio (the ratio of the outer projected area of the vehicle to the cross-sectional area of the tube) increases. Aerodynamic heating is caused by the vehicle friction with the surrounding medium at the high speeds. As the clearance between the capsule and the tube wall becomes smaller, more intense collisions and mixing of airflow occurs as well as more airflow viscous friction with the surface of the capsule, causing the temperature of the whole system to increase. A large amount of heat generation caused by the capsule can be harmful to the system's operation.

Detailed CFD (Computational Fluid Dynamics) thermal Analysis of the tubes structures should be carried on investigating the optimal blockage ratio to avoid the potential temperature increase that could arise from the aerodynamic heating of the vehicle at very high speed inside the tubes.

3.0. SECONDARY ELEMENTS DESIGN

In this section will be briefly described some of the secondary elements to be considered during the design of the Hyperloop infrastructure

3.1. EXPANSION JOINTS

Thermal expansion has been a problem with large tubular structures for a long time. Oil pipelines use various technologies to overcome this obstacle, with one such solution being expansion loops. The loops provide a necessary extension

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of piping in the perpendicular direction of fluid flow to absorb thermal expansion. Safer than expansions, they however occupy more space and they are impracticable solution for an Hyperloop system.

The *Hyperloop Alpha* white paper, while presenting the proposed route stretching from San Francisco to Los Angeles, considers slip-joints as an answer to this problem, however many of the technicalities have yet to be addressed. Considering that track, constructed from steel, and assuming standard values for thermal coefficient of steel and a temperature range of 0 °C to 40 °C, means that the track would need to expand by approximately 300 m to accommodate the full range of temperatures. Slip joints could be placed at the stations, but that would mean the joints and stations would need to be able to move by 300 m.

Another more feasible option is to space these out incrementally, which means incorporating several structural expansion joints along the track. They would be located over support piers or abutment seats.

The design of the optimal Hyperloop expansion joint must take in account three basic requirements:

- Accommodate horizontal large displacements;
- Ensure the operational "almost vacuum" status;
- Satisfy the continued functionality under earthquake design forces.

Depending on the displacement capacity needs the expansion joints could be manufactured using elastomeric bellows or a more complex telescopic design to accommodate larger displacements.

Another issued related to thermal loads is buckling stresses due to the difference in temperature between the top and the underside of the steel tube (temperature gradient). In any sunny area where Hyperloop is intended to deploy (Los Angeles, Dubai etc.), the top surface of the tube will heat up and hence expand more than the underside of the tube. This could transform the circular cross-section into a mushroom-like shape. This would not only affect the structural integrity of the tube itself, but also the internal components required to maintain smooth travel of pods and could cause contact between the pod and the tube.

3.2. SUBSTRUCTURES

The purpose of the tubes substructures is to bridge the height difference between the tubes and the ground (through bearing supports) and to transfer forces from the superstructures to the foundations taking system-related requirements into account. Concrete and steel designs are both acceptable columns even the concrete is undoubtedly the optimal solution. Better if used with post-tensioning

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technology. The foundations are generally made in concrete adopting a deep pile design to limit the settlements.

General Functional requirements

The influential functional requirements for guideway substructures are:

- The substructures must directly support the actions from the tubes structure via the support bearings and reliably transfer them to the foundations;
- Tubes equipment components, modules and ausiliary structures (e.g. safety fire escapes and maintenance structures) must be reliably incorporated;
- Tubes substructures must permanently guarantee the required positional accuracy of the superstructures.

General Design requirements

The following design requirements must be considered when designing the substructures:

- Vertical frequency analysis that will be performed during the design of the hyperloop structure shall consider the flexibility of bearings, shear keys, columns, and foundations; torsional frequency analysis shall consider them as well;
- Substructures permissible deformations along the three axes must be considered as part of the design; limitations required by norms of high speed rail or Maglev systems have strict limits that can be as low as L/4000). When the permissible deviations in the positions of substructures are exceeded (subsoil long term assessment, earthquake movements, etc.), readjustment of the support bearings is necessary for ensuring system compatibility;
- When designing the foundation system, the high loading velocity and dynamic forces (frequency, amplitudes) from the tube structures mist be also observed – extensive theoretical and/or empirical studies of the soil behavior must be required;
- Safety devices must normally be included according to the project-specific safety concept to prevent impact of vehicles and devices on crossing and parallel routes;
- Separate substructures for consecutive tube structures should be avoided.

Support Bearings

The design development of the tubes structure support bearings is to be selected in connection with the static layout of the complete superstructure and substructure system. Suitable supporting systems are to be selected in accordance with the static system of the tubes (e.g. simple supported vs continuous).

The determination of the support arrangement (sequence fixed-/loose supports) of tubes structures spans following on from each other and in connection with the installation of the support bearings requires verification of compatibility with the complete system. The vertical and horizontal stiffness must be adequate to make the system stable during operative conditions. In case of rare actions and

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combination of actions it is possible to guarantee the required positional stability via additional devices which are normally not required in normal operation (e.g. Lock-Up devices and Fail-Safe devices).

In case of use of moving friction-controlled bearings (e.g. sliding bearings or Friction Pendulum bearings) the friction coefficients accepted in the dimensioning of the bearings are to be indicated by giving their functions and value limits. The friction coefficient values given are to be proven and tested. The speed of movement of the supports (low speed-high speed) is to be taken into account in the theoretical estimation of the wear of the bearing support system (verification of serviceability).

Maintenance of support bearings

The support bearings are to be developed in such a way that the tube structures can be adjusted in the shortest possible time at the lowest possible cost in the case of subsidence. The degrees of adjustment are to be prescribed specifically for the project. If the admissible value limits of the deformations and displacements are exceeded, a balance should be aimed for by adjusting the supports. If this is not possible a simple exchange of the wearing parts must be guaranteed.

In the case of direct connection of the tube structures to the pier substructures (e.g. in the case of direct casting of the bearing steel plates to the substructures) the durability and safety is to be guaranteed by a robust and error tolerant design.

For carrying out repairs to supports the tubes should not be raised more than 5mm. The location of presses for raising the tubes structure is to be defined and marked on the tubes.

4.0. MATERIAL REQUIREMENTS

The selection of the most suitable material (or materials) is undoubtedly one of the fist challenges associated with the design of the tube. To match the expected low maintenance and great durability of the Hyperloop system, the tubes structure should be constructed of materials that have a longer life than conventional structures. Moreover, to make construction faster and less expensive, prefabricated support columns and tube spans should be considered.

Along with the mechanical properties associated on each structural material, there are some essential characteristics that the Hyperloop tube structure must perform.

Mechanical Properties

Of the three primary mechanical properties, strength, stiffness and damping, stiffness is expected to dominate any static analysis and is the primary design

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constraint. Dynamic loading effects increase the importance of structural damping characteristics for the overall tube design. The tendency for damping constraints to exceed stiffness constraints depends on the dynamic behavior experienced by the tubes. Passive damping of 2 % to 5 % should be achievable through proper material selection. The potential amount of damping possible could be managed with the use of active and passive devices (e.g. dampers) that could possibly be adjustable in function of the dynamic loads imposed by the speed of the vehicle to additional ride quality improvements.

Operational properties

A major technical challenge associated with the tube design is how to ensure that the entire length is kept airtight. Any ruptures or openings in the tube might result in a large pressure difference and a shock wave will propagate along the route. This essential property must be guaranteed in a long-term condition, as well as must be guaranteed also creep, shrinkage and relaxation. Other operational properties should include also high fire protection rating and magnetic inertness.

4.1. CONVENTIONAL MATERIALS

The civil engineering standards recognize two basic materials: Concrete and Steel. Each one of them has pros and cons that should be considered and evaluated for the Hyperloop superstructure.

Concrete

Concrete is a versatile material and has the main advantage to be easier to manufacture and is undeniable cheaper than steel. But it lacks tensile properties and needs thou the steel rebars to compensate this deficiency. It has somehow a shorter life than steel under several physical and chemical processes as well as certain environmental conditions that may deteriorate its resistance in a short period of time. Concrete is nowadays often used with prestressing technology, that improves in a more efficient and economical way the structural performance of the superstructure. One of the main disadvantages of the concrete is its porosity. Using the concrete for the tube structure could pose the risk of a leak due to potential outgassing that might compromise the sealing of the tubes during the service life. This issue although could be controlled with the adoption of sealing layer or special additive in the concrete mix.

Steel

Steel has a higher resistance than concrete; it has excellent tensile and compressive behavior but is way more expensive than concrete.

It is usually more durable than concrete even if, under certain environmental and chemical conditions could be easily deteriorated as well. Steel superstructures

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are usually lighter than concrete alternatives, but the material savings are often be offset by the complexity of manufacture, the steel costs, and usually they perform a reduced structural efficiency in the connection between superstructure and substructure. Steel has thermal expansion characteristics similar to that of concrete and therefore is an excellent reinforcing material for concrete. One of the problems associated with steel structures is the corrosion and magnetic interference potential.

4.2. COMPOSITES AND HYBRIDS

Composites

Fiber reinforced polymer, FRP, is the most promising of the composite materials for use in structural applications. Fibers typically used are boron, carbon, glass and aramid. Boron and carbon are extremely expensive. Aramid is somewhat less expensive but has low compressive strength. Glass (GFRP) is relatively inexpensive, has high strength, but is only one quarter as stiff as mild steel. For flexural design of the tube structures stiffness is likely to be the primary base of comparison between CFRP (Carbon), especially the high modulus (HM) and high modulus (UHM) CFRP, though roughly equal or even superior to mild steel in stiffness, has three to four times the strength. Major drawback of all those composites is often related to the directional e strength of the properties. Unlike isotropic materials (like steel) the properties of GFRP or CRFP depend on the layouts of the fibers.

Another viable solution of composite material is the adoption of the concrete composite structure with a thin metal layer. Because the inside steel layer will want to be pushed away from the concrete layer, special attention needs to be directed to securing it in place. This may be a challenge to avoid. The overall thickness of the tube may be larger with this composite structure, but the cost will be less than a steel tube since concrete is much cheaper than steel. This structure will have large compressive strength to allow for a more intense vacuum degree. A stainless steel layer could also be added to the outside of the concrete to help mitigate damage and corrosion. This layer would tend to be pulled against the concrete layer, making the fastening much easier.

Hybrids

One of the most successful hybrid materials that is currently being adopted in various civil engineering project is called Ultra High-Performance Concrete (UHPC).

This material is basically a concrete that uses a relatively high binder ratio, has a water-to-cement (w/c) ratio of 0.24 and lower, and has a compressive strength in excess (150 MPa). Low matrix porosity and high particle packing density leads

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to significantly higher durability at a similar unit weight compared to conventional concrete. The addition of discontinuous fibers reinforcement (organic or steel) leads to significantly higher ductility, durability, high flowability (self-consolidating), higher mechanical properties (high tensile properties) and durability. The UHPC is usually manufactured with steel fibers although there are also commercially available some varieties that use glass fibers that could reach even higher strength and durability properties.

Compared to traditional concrete, the UHPC reduces substantially the typical degradation like outgassing and microcrackings due to the low water content and the high tensile properties.

5.0. DYNAMICS

The current state-of-practice for the design and dynamic behavior assessment of the typical high-speed rail infrastructures is comprehensively studied in several norms and codes around the world. However, the dynamics is usually explored for train speeds that often reach no more than 200 km/h. Chinese codes issued by the Ministry of Railways of PRC refers to 350 km/h as top speed while the Maglev design basis guideway (*Magnetschnellbahn Ausführungsgrundlage Gesamtsystem*) from the EBA – German Federal Railway Authority, gives some very useful indication and guidelines for speed up to 450 km/h. The operative speed of an Hyperloop system is more than double of the highest speed ever considered in any actual released code so there is a need to set some rigorous dynamic analysis to understand the dynamic interaction between the tube structure and the vehicle. At Hyperloop speed a flexible tubes structure is usually less expensive but could cause a very complex interaction problem and could affect ride quality as well. The scope of the dynamic analysis is to optimize the whole Hyperloop system: the vehicle with its suspension and active control characteristics in one side and the tubes structures with its flexibility in the other side. The elements essential of an interaction model are as follows:

1) Vehicle Dynamics;
2) Vehicle Suspension and Guidance;
3) Surface Roughness;
4) Tubes structure Dynamics;
5) Bearings Support and Soil Dynamics.

As the vehicle travels inside the tube, suspension system forces and guidance system forces, which causes various linear and rotational accelerations. The suspension system responds to vehicle motion, the tubes structure dynamics and surface irregularity. The tubes structure forces the bearings support and they transfer

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(and filter sometimes with specific stiffness and damping) the loads through the substructures and interact eventually with the soil dynamics. These systems interact with each other through time varying interfaces. The strongly coupled process is extremely complicated.

Since the details of the computational dynamic analysis is beyond the scope of this paper, here it will be shown the civil engineering approach in considering the dynamic effects on the tube structures and some reference to vehicle dynamics.

5.1. RESONANCE AND DYNAMIC AMPLIFICATION FACTOR (DAF)

According to the fundamental theorems of structural dynamics, when a moving load (or a train of moving loads) travels over a bridge (or tubes structure in our case), the loading frequency (basically dependent on the vehicle speed and bridge span) will change with the vehicle speed and a resonant vibration will occur when the loading frequency coincides with the natural frequency of the structure. The strong vibration induced by the resonance not only directly affects the working state and serviceability of the structure (higher stress and deflections), but also reduces the running safety of the vehicle, diminishes the riding comfort of the passengers, and sometimes even destabilizes the structure itself. Therefore, it is necessary to develop methods to predict the resonant speeds of the running loads and to assess the dynamic behavior of the structure under resonance conditions.

Dynamic Amplification factor

The dynamic amplification factor (DAF) or sometimes called also impact factor IM, is an important parameter that it is often used in the codes during the design and assessment of the dynamic behavior of bridge structures in the absence of detailed dynamic analysis, simply by magnifying static deflection. This parameter is defined as the ratio of the maximum mid-span deflection of the bridge caused by dynamic conditions to the deflection induced by the static loads. Resonance is often related with the maximum DAF. In general, DAF is not a deterministic value and must be estimated through probabilistic methods.

Several numerical simulations performed with MATLAB-SIMULINK, or even using more focused FE bridge software like SAP2000 to perform time-dependent nonlinear modal analyses with an emphasis on tube dynamic deflection under a moving vehicle at various velocities, show that the DAF of the vertical deflection and bending steadily increase (after reaching a speed threshold) in proportion to the vehicle speed. In addition, it is observed that the DAF for the deflection is almost the same as that for the bending moment at the low and medium speed, but the deflection's DAF is higher at the high speed. Some established code

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references suggest, for simple supported span structural scheme, to use maximum DAF:

- AASHTO LFRD: DAF=1.33 (*not depending on speed or span*)
- Transrapid (DE): DAF=1.56 max speed 500 km/h span=25 meters
- General Atomics: DAF=1.50 max speed 200 km/h span=36 meters

For the hyperloop system, with a range of speeds up to 1200 km/h and a span of 25 meters some studies evaluated the theoretical DAF close to 1.8.

This large value of DAF and the lack of dedicated studies of moving vehicles at very high speeds suggests that detailed dynamic analysis should be performed with robust and reliable analytical models since the early stage of the design, because the basic parameters of spacing and tube stiffness are strictly involved. The model should take realistically in account at least the tubes structure (material, geometry and spacing), stiffness, damping, single vs continuous spans and hopefully also some information related to the substructures like geometry and stiffness. The model should investigate the dynamic behavior of the system both at low and high travel speed.

5.2. VERTICAL DYNAMIC ACCELERATION

For the level of speeds that an Hyperloop system can reach, the ride quality is of highest significance since the extremely high operating speeds may result in discomfort to the passengers. Together with the evaluation of the dynamic behavior of the tubes structure, the vertical acceleration of the vehicle should be carefully evaluated. While for the evaluation of the dynamics of the tubes structures (and DAF calculations) the vehicle might be represented with just moving forces, in this case the analytical modelling of the vehicle must include its lumped mass and two suspension systems: the primary or magnetic suspension comprising of primary stiffness (k_p) and primary damping (c_p) and the secondary suspension comprising of secondary stiffness (k_s) and secondary damping (c_s). The primary suspension acts between the levitation frame and the tubes structure, while the secondary suspension is between the levitation frame and the vehicle. The suspension of such a vehicle must be designed not only to perform the role of guidance and support but also to isolate the vehicle from any random disturbances arising from track irregularities (roughness of the track). Using Signal processing Tools provided in SIMULINK, a Gaussian white noise could be generated and then passed through a specified infinite impulse response (IIR) filter to get the desired guideway irregularity. The vehicle vertical acceleration magnitude is an indication of vehicle ride quality and it should be always verified that is will stays within the limits of human comfort. The range of acceptable vertical acceleration is -0.6 ms^{-2} to $+1.2$ ms^{-2}.

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5.3. EXTERNAL DYNAMIC LOAD - EARTHQUAKES

Potential earthquake dynamic loads on the Hyperloop infrastructure vary between geographic regions and they are regulated in each region by technical rules and standards. The actual civil engineering design practice is to provide sufficient strength and ductility capacities to the substructure components (columns, foundation, bearings and expansion joints) to meet the service and seismic performance requirements.

Despite better detailing and confinement in modern structures leading to enhanced damage tolerance and reduced collapse susceptibility, significant damage to this kind of infrastructure has occurred following seismic events in all the sides of the world. Such damage requires extensive repair or complete replacement of the columns and superstructure. To guarantee post-earthquake serviceability and reduce the repair costs, research efforts in recent years have been directed towards the development and implementation of innovative materials, supplemental damping and energy-dissipation mechanisms, and seismic response modification techniques for new and existing structures.

One of these seismic performance enhancement strategies, particularly effective for sites with medium to high seismic hazard or directivity effects, is seismic isolation.

The concept of seismic isolation is particularly interesting for the Hyperloop infrastructure, because of a series of potential advantages related to its specific structural characteristics. The high degree of protection given by a seismic isolation system will ensure the continued functionality and minimize the damages into a few mechanical elements that may be easily checked and replaced, if need to be.

In addition, mostly of the mass of the Hyperloop superstructure is concentrated on the tubes structure, and this part of the structure is designed to remain fully elastic under seismic input.

The base isolation technology has the following characteristics:

- Flexibility to lengthen the period of vibration of the superstructure to reduce seismic forces in the substructure;
- Energy dissipation to limit relative displacements between the superstructure above the isolator and the substructure below;
- Adequate rigidity for service loads (e.g. wind and operational accelerations) while accommodating environmental effects such as thermal expansion, creep, shrinkage and eventual prestress shortening.

The design of the isolation system should be taken in account and interact with the Hyperloop dynamics, although for the preliminary design stage, simplified lumped mass models and non-linear analysis in the time domain, using spectro-

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compatible accelerograms, could give some direction for the choice of the optimal design.

Earthquake Early warning systems

Japan is one of the regions of the world that is highly exposed to earthquake risk. In the same time, it has a dense rail network of trains, and many of them are running at operative high-speed. To slow down or even stop the trains during an earthquake as soon as possible, they developed an early warning system based on the detection of the seismic P-waves at distant stations from the tracks. Once detected, the system sends a warning signal to the general control center that will alert the train before the S-waves arrive at the train tracks. This efficient system could be surely adopted in the Hyperloop infrastructure to enhance the safety during a strong seismic event.

5.4. EXTERNAL DYNAMIC LOAD - WIND

Generally, the wind effect depends on the geographical position of the district, its altitude from the sea level, the local topography and to some geometrical characteristics. As opposed to the wind force evaluation of any other transportation technology, the hyperloop system has the big advantage that the vehicles are not directly exposed to the wind pressure or gusts or storms or any other atmospheric phenomena. As most of the structures the wind-induced resonant vibrations might be negligible during the preliminary design stage. For the tubes structure, as well as the ausiliary and substructures, the wind responses can be determined using the procedures applicable for static loads. More detailed dynamic analysis is required during the design stage to investigate and eventually mitigate the dynamic effects of the wind.

Vortex-shedding

When a fluid flows over a slender structure, alternative vortices are shed over its sides resulting in the generation of an inconsistent force due to low pressure regions being created in the direction normal to the flow of the fluid. This systematic formation pattern of vortices is referred to as the *Von Karman vortex street*.

When the shedding frequency of the vortices (depending on *Strouhal* and wind speed) is in resonance with one of the natural frequencies of the tubes structure, large amplitude vibrations may be expected in a plane normal to the flow. The phenomenon of vortex shedding is generally significant for the lower natural frequencies of the structure, but for flexible structures having a low damping ratio, this might occur at higher frequencies as well. The vortices will be shed by the flow of wind in the downwind side and large amplitude vibrations may result if the natural frequency of tube structures is in resonance with the shedding frequency.

The vortex shedding phenomenon generally occurs at steady wind flow conditions at a critical velocity. The periodic vibrations of the shed vortices may lock-in with the natural frequency of the structure causing high amplitude vibrations in the transversal plane to the wind flow. The oscillations generated by vortex shedding can be quite severe to cause fatigue cracks in the structures

The *Strouahl* number 0.2 is usually referred to free-air vertical element while the Hyperloop tubes are relatively close to the ground and the structural scheme is a continuous span rather than a single cylinder. A more realistic approach is recommended, which could be developed using software platforms like ANSYS CFD and imposing the boundary conditions related to the position and orientation of the tubes, both along straight line and curved one. The numerical simulations should interact with the dynamics related to the levitation and guidance system and it should be explored at different vehicle speed as well.

CONCLUSION

Musk's *Hyperloop Alpha* white paper provided an innovative spark to transportation technologies when introduced the Hyperloop. It is clearly seen that it could be considered as an evolution of the Maglev transportation system, which share with Hyperloop many technical features and advantages (and design limitations as well). Maglev is an already proven technology seen operational in high speed train systems throughout the world and more consideration should given to using it for the Hyperloop technology.

While nowadays Hyperloop is often proposed and described as the best transportation solution, with clear goals for the functionality of the system and undeniable economic advantages for the community, more thorough engineering analysis is required to assess its technical viability. In this paper the main subsystems related to the infrastructure design were broken down into its fundamental parameters and governing physical principles. These were then briefly analyzed to evaluate their effect on both their corresponding subsystem and the overall Hyperloop performance.

Although the technical aspects of the Hyperloop are quite challenging, it will be surely feasible to build an operational system. This will require a substantial amount of prototyping and design refinement. The basic indications and tentative approach concerning the design of the civil infrastructures could be used to create a more developed foundation to advance the Hyperloop work. While technical solutions will be found to ensure high performance and passenger satisfaction, it will be other aspects that have the potential to keep the Hyperloop from leaving the concept stage. Economics and community pressures will dictate the future of the Hyperloop.

Been involved with the civil infrastructure design of an Hyperloop system I see the possibility of one day connecting any two major cities across the world by less than a couple hour capsule ride very inspiring.

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