Design of A Control Mechanism of A Maglev Carriage for Space Launch and Its Dynamic Stability

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Keywords

Maglev dynamics, space launch vehicle, control mechanism.

Abstract

This paper presents the development of a control mechanism and the dynamics analysis of the carriage for a space launch Maglev system based on the Lawrence Livermore National Lab (LLNL) Inductrack. A hybrid control mechanism is proposed to effectively cover wide range of the operation speeds. Then, the dynamic stability is derived and the computer simulation is also performed in order to identify the intrinsic dynamic characteristics. The results confirm that the Maglev system is inherently unstable and needs a control system for its stable ride.

1 Introduction

Maglev is a proven technology for high-speed transportation systems [1]. By extending this technology, it becomes attractive to apply Maglev as a part of the launch assist system for future spacecraft [2]. The vehicle would be mounted to a carriage on a horizontal Maglev track and accelerated to a predetermined speed of about 1000 km/h. The vehicle would then be released from the carriage and fly as a normal airplane to reach space altitude. The dynamics of the magnetically levitated and propelled carriage/payload system are complex and inherently unstable. Dynamically this is highly non-linear system having six degrees of freedom (6-DOF), some of which are coupled. The main focus of this work is design of the control mechanism and exploration of the dynamic motion of the Maglev system's carriage. This required the development of a 6-DOF mathematical model, which was then analyzed using the Matlab®/Simulink® software. This dynamic model provides insight into the effects of various carriage and payload combinations. This information provides a base for future studies in the area of Maglev technology. The reference used is the repulsive-force system developed at the Lawrence Livermore National Laboratory which is currently located at the University of Central Florida.

2 Maglev System

The track developed by the Lawrence Livermore National Laboratory (LLNL), Inductrack, uses a special arrangement of magnets called a Halbach array. This array causes the magnetic field lines to combine and form a concentrated field below the array and cancel on the top [3]. An infinite number of bar magnets would produce a sinusoidal variation of field at a constant distance from the bottom of the array. In this application the array contains five magnets which closely approximates the sinusoidal variation.

As shown in Figure 1, the unique feature of the Inductrack concept is that there are lower magnet arrays mounted on the carriage to act on the underside of the track as well as on the top. The lower arrays are mounted on each side at a 45° angle to enhance the stability of the carriage in both the vertical and lateral directions.

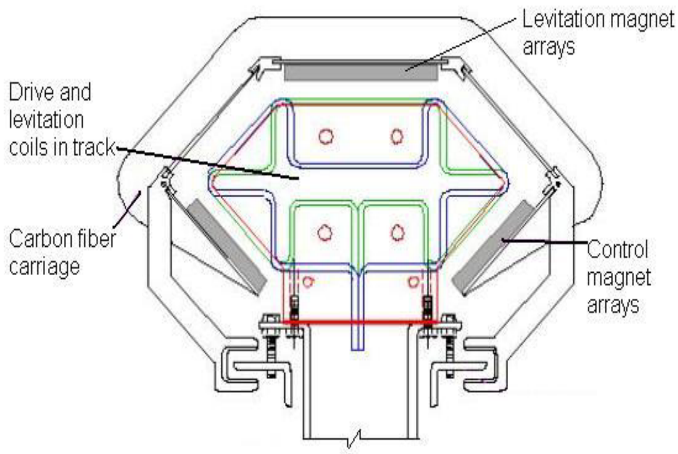

Figure 1, Current Inductrack Configuration

3 Control Mechanism

Pre-levitation: The carriage needs an initial velocity before it levitates. To control the movement of the carriage prior to levitation, an arrangement of load and guide wheels can be used. These will keep the carriage properly positioned, to ensure that the initial acceleration is efficient and controlled. These wheels hold the carriage in position until levitation velocity is achieved.

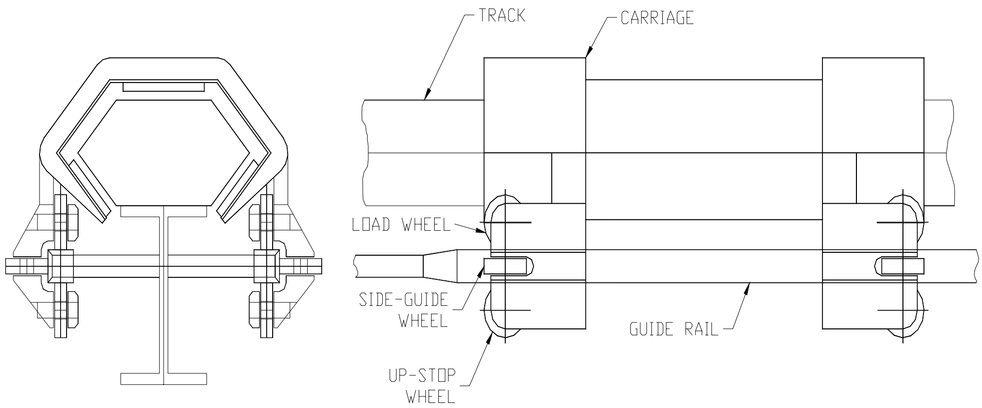

Figure 2, Guide Wheel Arrangement

After levitation, this arrangement then functions to prevent the carriage from contacting and damaging the coils in the track. This would be easily accomplished by tapering the track to a smaller size, away from the wheels. This would have no moving parts, versus any scheme that would retract the wheels.

Magnetic Force Control: To control stability at low speeds, movable lower magnet arrays is one possibility. One example of this system would add a pivot above the magnet array and place actuators above the pivot to move the arrays in and out as required. The movement will need to be restricted so that the magnets cannot contact the track. The advantage of this is that there would be minimal design changes, as opposed to doing this electrically in the track. There would be a weight penalty added to the carriage for the actuators, power supply, and mounting arrangement.

Aerodynamic Control Surfaces: At higher speeds, it is expected that the movable magnet arrangement will not be adequate to control the carriage. Since the carriage is actually flying at this point, flight control surfaces similar to an airplane wing would provide stability without major development. These would be attached to the carriage and be independent of any control surfaces that are part of the payload. They would be used to control the carriage prior to and after payload separation. One area of question however is the use of aerodynamic control surfaces at mach speed at ground level. The effects of this will need to be investigated prior to actual design of the system. Also when these surfaces become active, most likely based on speed, the movable magnet arrays would most likely need to be locked in a predefined position.

4 Control Schemes

Only few research works have been reported on the control and sensing of Maglev vehicles. While adding the lower arrays has improved stability, there is still some work to be done in this area. It has been noted that the carrier still experiences some instability, especially during initial levitation. The method of control proposed by making the lower magnet arrays movable is one possibility to add additional stability to the carriage. These could be driven by several methods, such as electrical actuators or hydraulic or pneumatic cylinders. This control system would be very useful at lower speeds. At higher speeds however it is questionable if the reaction times would be quick enough for accurate control.

At higher speeds the proposal to use aerodynamic control surfaces to control the movement of the carriage is possible. These would be wings attached to the carriage to control its motion both prior to and after payload release.

Since the force from the arrays is dependent on distance, they act as springs to center each end of the array. The lower arrays function to increase the spring force from the upper array to a usable and controllable magnitude. This spring force can be increased or decreased by adjusting the forces generated by the arrays through adjusting the area, changing magnetic field strength, or modifying the nominal distance to the coils. Adjusting area can be accomplished by changing magnet size, adding additional arrays, or by controlling the effective area.

Roll is controlled to a lesser degree by these arrays, as there is no significant force differential between left and right sides. It is possible for the carriage to assume an attitude where it equalizes itself without returning to its neutral position as shown in Figure 3. Roll will best be controlled by an active control system with the current geometry. For this reason, an active control system, or further arrays acting on either the vertical track-mounting surface, or on the horizontal wheel guide way will be necessary to fully control roll.

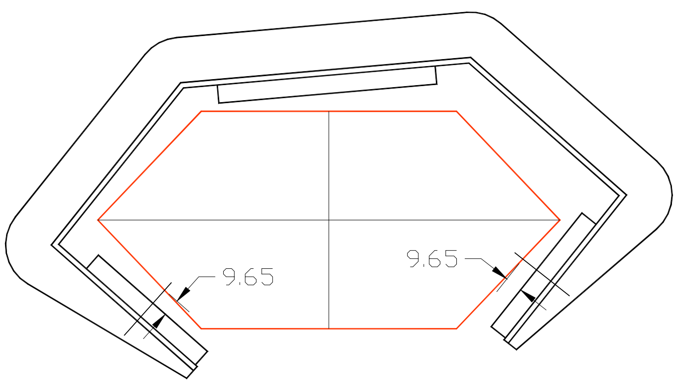

Figure 3. Roll Control

5 Nonlinear 6 DOF Dynamics

The Maglev carriage can be modeled as a rigid body with six DOF. The coordinate system for the inertial reference frame is set up with the x-axis in the horizontal direction of travel (DOT), the y-axis lateral across the track and the z-axis in the vertical direction. The orientation of the three linear velocities u, v and w and three rotation velocities p, q and r are shown below in Fig. 3.

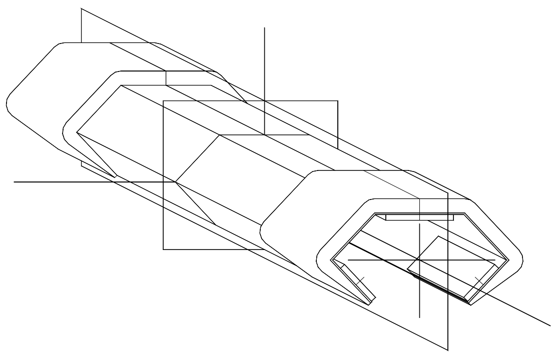

Fig 3. Maglev Carriage and Its Coordinate System

Kinematics

The motion of the carriage-fixed coordinate system is described relative to the track-fixed coordinate system. The general state of motion is described by the following quantities;

$\boldsymbol{\eta}_1 = \{x \quad y \quad z\}^T$, inertial position,

$\boldsymbol{\eta}_2 = \{\phi \quad \theta \quad \psi\}^T$, inertial orientation,

$\mathbf{v}_1 = \{u \quad v \quad w\}^T$, body-fixed linear velocity,

$\mathbf{v}_2 = \{p \quad q \quad r\}^T$, body-fixed angular velocity,

$\boldsymbol{\tau}_1 = \{X \quad Y \quad Z\}^T$, external forces,

$\boldsymbol{\tau}_2 = \{K \quad M \quad N\}^T$, external moments

Using this convention, the equations of motion can be derived by:

$$X = m[\dot{u} - vr + wq + z_G(pr + \dot{(q)})]$$
$$Y = m[\dot{v} - wp + ur + z_G(qr - \dot{p})]$$
$$Z = m[\dot{w} - uq + vp - z_G(p^2 + q^2)]$$
$$K = I_{xx}\dot{p} + (I_{zz} - I_{yy})qr + (r^2 - q^2)I_{yz}$$
$$- m[z_G(\dot{v} - wp + ur)]$$
$$M = I_{yy}\dot{q} + (I_{xx} - I_{zz})rp + (qp - \dot{r})I_{yz}$$
$$m[z_G(\dot{u} - vr + wq)]$$
$$N = I_{zz}\dot{r} + (I_{yy} - I_{xx})pq - (\dot{q} + rp)I_{yz}\,.$$

These equations are based on the assumption that the carriage body, payload and magnet arrays can be modeled as a single rigid body. This approximation may or may not be appropriate for the Maglev system, based on the ultimate construction of the carriage, payload and the payload mounting method. These variables are dependent on the ultimate design of these components. Since the ultimate configuration of these components cannot be fully anticipated at this point, this assumption is used as a starting point in the analysis of the Maglev system.

6 Simulation

In this section the forces affecting the stability of the carriage will be examined. This will require an analysis of the change in the forces due to a perturbation from the nominal position of the carriage. For the carriage to be stable, these forces will need to self center the carriage, and any oscillations will need to decay over time. These forces are produced not only by the top array, but also by the lower arrays.

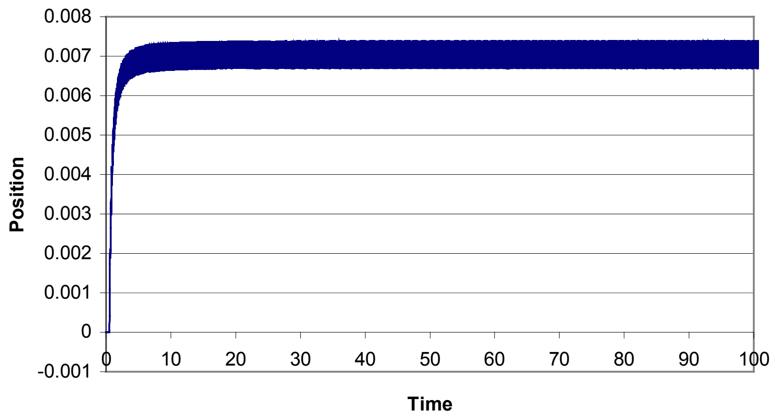

Fig. 4. Vertical Position Without Perturbation

As can be seen in Fig. 4, the carriage oscillates around the levitation height of .007m without any perturbation forces.

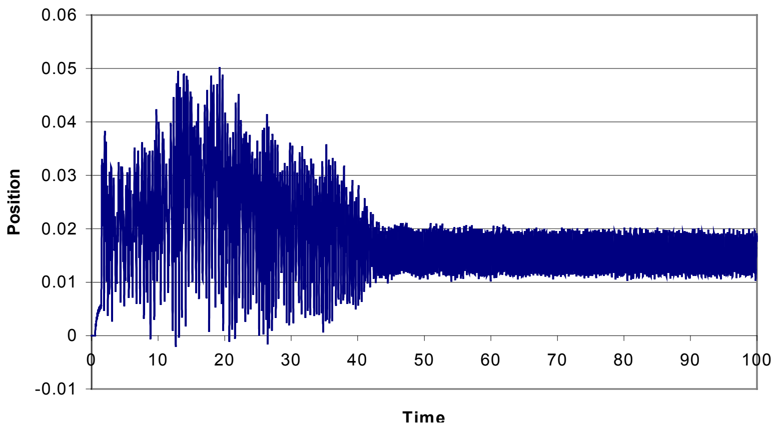

Fig. 5. Vertical Position with Pitch Perturbation

With a pitch perturbation, the vertical oscillation initially has a large magnitude, which reduces to a lower magnitude centered around .014m. The magnitude of this oscillation is greater than before, ±.004m versus ±.0005m without the perturbation. This illustrates the need for an active control system to correct for perturbations that are introduced into the system.

Further work is needed in this area. The computer model needs to be verified against the test track. Also the control schemes discussed need to be developed and implemented.

7 Conclusion

In this research, a control mechanism of the LLNL Maglev was studied as well as the dynamic motional characteristics. The 6 DOF dynamics of the vehicle are complex and inherently unstable. In order to compensate the dynamic instability, a hybrid control system was developed to effectively cover wide range of the operation speeds. The future work will be design of an effective control law for the developed control mechanism.

References

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